WHITE PAPER

SALMONID TRAVEL TIME AND SURVIVAL RELATED TO
FLOW MANAGEMENT
IN THE COLUMBIA RIVER BASIN

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September 1999

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INTRODUCTION

Known world-wide for its anadromous Pacific salmon, many of the Columbia River's salmon stocks are now at critically low levels, and most are listed as threatened or endangered under the Endangered Species Act (ESA). Although overfishing had substantially depleted some stocks by early in the 20th century, direct and indirect losses due to environmental modification have had the greatest, long-term effect on stock viability (Williams 1989). Some of the largest loses resulted from dam development (Raymond 1988, Williams 1989, NMFS 1991). The deleterious effects of dams are numerous. Dams block access to historic spawning areas, cause direct and indirect losses to fish which pass through them, form reservoirs that provide suitable habitat for a new assemblage of fishes, or increase existing habitat for existing stocks, including predators, and alter the magnitude, timing, and quality of flow.

River flow in the Columbia River Basin was altered substantially by the construction of 28 major dams used for storage and hydropower production. By 1979, the total storage capacity had reached nearly 40% of the Columbia River's annual discharge (Pulwarty and Redmond 1997). As a consequence, storage of water for winter hydropower generation and spring flood control had altered the natural runoff substantially (Table 1, Fig. 1).

The added number of impoundments increased the total cross-sectional area of the river which led to decreased water velocity and turbidity. These conditions led to increased travel time and subjected the smolts to greater exposure to predators and other factors of mortality (Raymond 1979, 1988; Williams 1989). The reservoirs have also substantially modified the river's thermal regime. The large mass of stored water (~ 48 million-acre-feet [Maf]) has created thermal inertia making the river slower to cool in the fall, slower to warm in the spring, and moderates the river's temperature extremes. The increased travel time, reduced spring flows, and altered thermal regime also changed the timing of fish entering the estuary and ocean environments. Snake River juvenile fall chinook salmon which historically migrated primarily in May and June prior to reservoir construction were particularly affected by the change in thermal regime. They now migrate principally in late June, July, and early August (Park 1969, Krcma and Raleigh 1970, University of Washington, DART data-base, 1996 - 1999). The change in migrational timing places these fish in the river at times and under conditions to which they are not well adapted.

Although mortalities of adult fish were observed under high spill conditions, the losses were not sufficient to affect the overall viability of chinook salmon *(Oncorhynchus tshawytscha)* stocks (Junge 1966, Merrell et al. 1971, Gibson et al. 1979). However, direct juvenile salmon mortality had increased sufficiently to significantly decrease adult returns. As an example, the Snake River Basin adult spring/summer chinook salmon returns (based on estimated numbers of recruits to the mouth of the Columbia River) decreased from an average of 76,850 for the years 1962 to 1968 to 13,175 for the years 1982 to 1988.

Concerns over these rapid declines led Congress to pass the Pacific Northwest Electric Power Planning and Conservation Act (NWPPCA) in 1980. The NWPPCA formed the Northwest Power Planning Council (NPPC) and charged it with, among other things, developing and

Table 1. Columbia River outflow (kcfs) at The Dalles Dam (from A.G. Crook Co., 1993,
Adjusted Streamflow and Storage, 1928-1989; COE Annual Fish Passage Reports,
1990-98).

Year	May	Percentage decrease from 1928-72	June	Percentage decrease from 1928-72	July	Percentage decrease from 1928 -72
1928 - 72	344	0	446	0	278	0
1973 - 98[a]	273	21	271	39	178	36

[a] Million-acre-ft (maf) of storage increased in 1973 with construction of Mica (7 maf), Libby
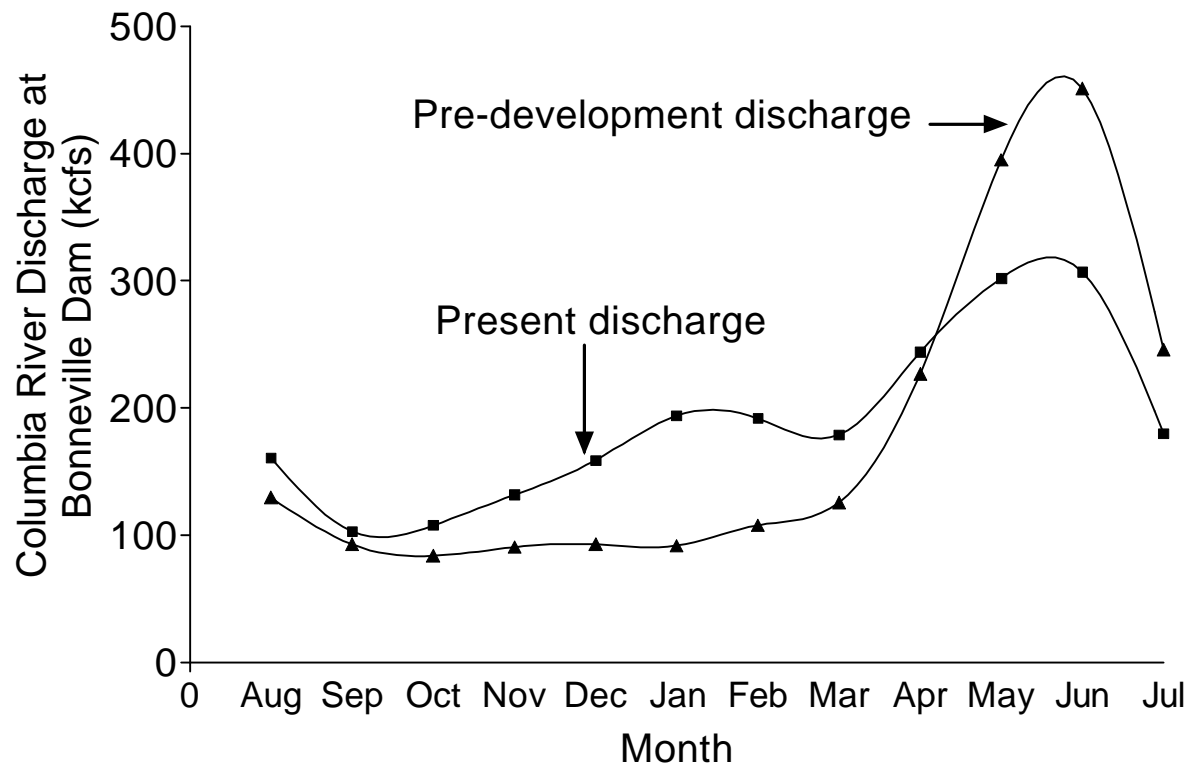(5 maf), and Dworshak (2 maf) Dams.

Figure 1. Average monthly flows at Bonneville Dam under present operating conditions of the Columbia River hydropower system compared to flows that would have occurred if no storage reservoirs were in place.

implementing a program to offset the effects of dams on salmon. The first Columbia River Basin Fish and Wildlife Program adopted a "water budget" for flow augmentation in 1982. This program specified that a regional group of fish and wildlife managers could utilize a volume of water in Federal Snake and Columbia Rivers storage projects to increase flows to benefit salmon. Following the continued decline of wild populations of salmon during the 1980s, petitions were filed in 1990 to list Snake River salmon populations under ESA. In 1992, the National Marine Fisheries Service (NMFS) listed Snake River populations of sockeye *(O. nerka)*, and spring/summer and fall chinook salmon.

The NMFS is charged with protecting anadromous fish listed under ESA. Section 7 of the ESA requires NMFS to consult with federal agencies on actions that may affect the continued existence of listed species. In 1995, NMFS concluded a consultation with the U.S. Army Corps of Engineers (COE), the U.S. Bureau of Reclamation (USBR), and the Bonneville Power Administration (BPA) on operation of the dams and reservoirs that comprise the Federal Columbia River Power System (FCRPS). The NMFS (1995) Biological Opinion (1995 BiOp) concluded that the agencies' proposed operations jeopardized the continued existence of Snake River chinook and sockeye salmon and that the system was unlikely to meet the biological requirements of these species unless there were major modifications in the migration corridor to significantly improve survival. A series of immediate actions were specified in the 1995 BiOp to improve salmon survival in the interim while further studies were conducted and actions considered to ensure the fishes' long-term survival.

One of the actions prescribed in the 1995 BiOp was modification of reservoir operations to increase the probability of achieving specific seasonal flow objectives to benefit downstream migrant juvenile salmon through the Snake and Columbia River systems. These objectives (Table 2) were somewhat modified in 1998 (NMFS 1998) to extend protections to recently listed steelhead *(O. mykiss)* evolutionarily significant units (ESUs). The present flow-management program uses two strategies: limit the winter/spring drawdown of storage reservoirs to increase spring flow and the probability of full reservoirs and draft from storage reservoirs during the summer to increase summer flows. To meet the first strategy, the FCRPS storage reservoirs are operated to achieve, to a high level of probability, water surface elevations within 0.5 ft of the flood control rule curve by April 10 and to refill by June 30. Prior to the 1995 BiOp, FCRPS storage reservoirs were routinely drafted well below these levels to maximize the hydropower generation during the fall and winter. To meet spring flow objectives may require occasional reservoir drafting, but flow objectives are primarily met through limiting winter drafting and rates of reservoir refill. During the summer, FCRPS storage reservoirs are drafted as necessary, but not more than specified limits, to attempt to meet the summer flow objectives and to provide colder water.

Although dams have had a number of effects on salmon survival, this paper will only focus on how dams affect river flow and how that flow is managed in the Columbia River Basin to improve, where possible, salmon migration and survival.

Table 2.   Flow objectives (kcfs) as established by NMFS (1995) and modified by NMFS (1998).

Season	Snake River at Lower Granite Dam		Columbia River at McNary Dam		Columbia River at Priest Rapids Dam	
Spring	(4/3 - 6/20)[a]	85 - 100	(4/20 - 6/30)[a]	220-260	(4/10 - 6/30)	135
Summer	(6/21 - 8/31) 55[a]	50 -	(7/1 - 8/31)	200	NA	

PHYSICAL WATER PROPERTIES AFFECTED BY FLOW

Flow (or discharge) is a measure of a volume of water moving past a point at a specified rate. In the Columbia River Basin, the common unit of measurement is cubic feet of water per second (cfs). Flow affects physical water properties that in turn can influence fish survival. Primary among these are velocity, temperature, and turbidity. Water velocity is directly affected by flow, whereas water temperature and turbidity are indirectly influenced.

Water Velocity

The velocity of water is determined by the area through which the flow passes. The same flow passing through a smaller area will create a higher water velocity than if it passes through a larger area. Water particle travel time (travel time = distance/average velocity) is directly proportional to water velocity. Construction of the hydropower system substantially changed water particle travel time under conditions with similar flow (Fig. 2). Prior to major reservoir development, the average water depth (and therefore cross-sectional area) increased as flow increased, thus increasing flows did not produce proportional increases in water velocity. In the present hydropower system, the mainstem reservoirs in the migration corridor are maintained at a relatively constant elevation, regardless of discharge. Because the cross-sectional area is virtually constant, water velocity varies more proportionately with discharge than it did prior to dam development.

Water Temperature

In general, water temperature changes over time as a result of heating and cooling processes such as solar radiation, atmospheric convection, or conduction. The larger the volume of water and the shorter the duration of the heating or cooling mechanism, the smaller the temperature change. Increasing flow has the effect of reducing the rate at which water temperature is changed because the volume of water is increased. However, in the specific case of flow management, increasing flow can have complex effects on water temperature. For example, if the augmentation water is warmer than the receiving water, then flow augmentation will increase water temperatures in the mixing zone proportionate to the flow of the two water sources. However, in the summer, by increasing the total volume of water subject to solar and atmospheric heat inputs, the rate of temperature increase from the mixing zone downstream would decrease. When the augmentation water is cooler than the receiving water, water temperature of the receiving water is decreased through the mixing zone and the rate of temperature change is decreased by the additional volume of water subject to the heat input.

Turbidity

Turbidity is a measure of light absorption in water caused by suspended matter. Turbidity is ecologically important as it influences, among other things, depth to which photosynthesis can proceed and visibility of sight-feeding fishes (Petts 1984). In natural streams there is generally a direct relationship between discharge and turbidity, although that relationship can change
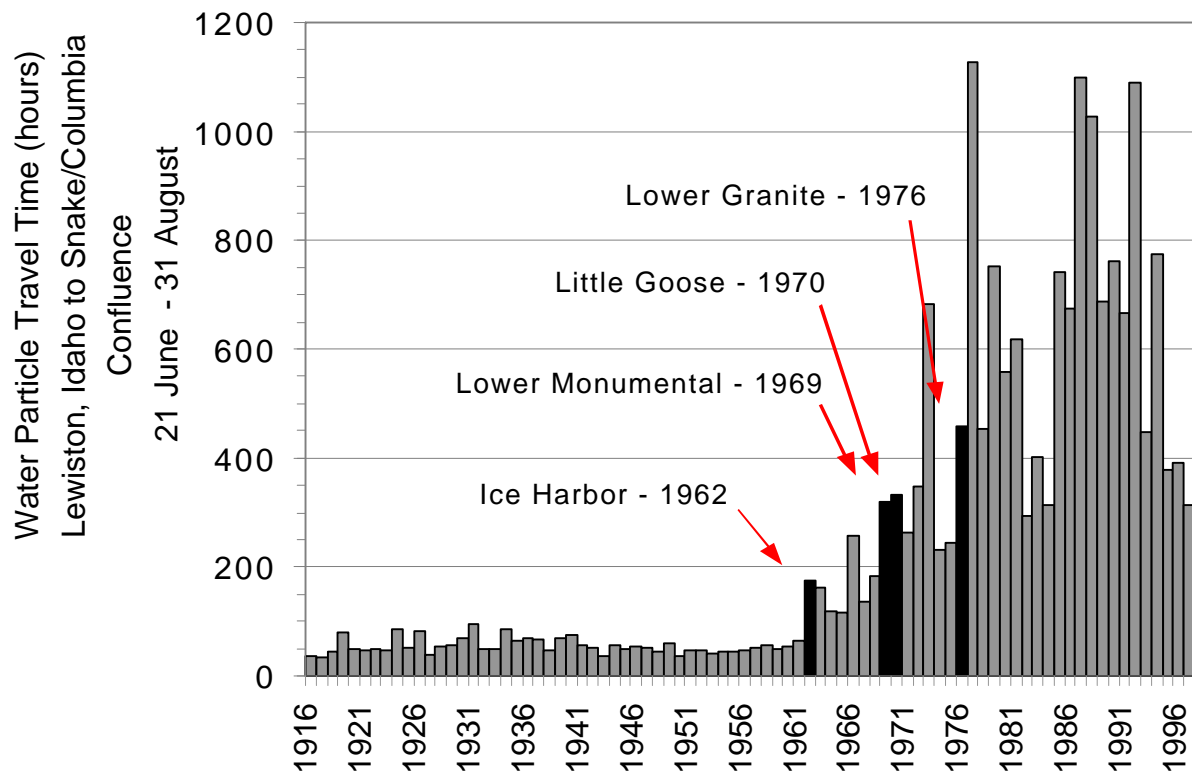
Figure 2. Estimated seasonal average water particle travel times from Lewiston, Idaho to the Snake and Columbia River confluence during the summer outmigration season including effects of lower Snake River dam development (After Dreher 1998).

seasonally. Large reservoirs, particularly the storage reservoirs associated with the Columbia River hydropower system, greatly change turbidity and other seston (suspended particles) transport characteristics of rivers. Reservoirs function as large settling basins. They lower water velocities and turbulence, thus allowing larger solids to settle out of suspension. The high residence times of water within some reservoirs also afford an opportunity for processing the particulate organic debris component of the seston load. As a result, turbidity downstream from large reservoirs can fall to just a fraction of inflow turbidity (Soltero et al. 1973). Further, turbidity in downstream areas are generally the result of colloidal and buoyant materials which can remain in suspension for long periods. Also, because of the increased opportunity for photosynthesis (primary production) in reservoirs, it is not uncommon for seston loads downstream from large reservoirs to contain similar or even higher concentrations of organic matter than incoming waters (Lind 1971). In some cases, suspended organic matter may increase to several times that carried by the river upstream from the reservoir (Spence and Hynes 1971), and may even result in an increase in turbidity at times of low river discharge (Décamps et al. 1979). However, since the mainstem Snake and Columbia River dams are flow-through projects, their effect on turbidity levels are reduced (Ebel et al. 1989).

EFFECTS OF FLOW ON JUVENILE SALMON

The magnitude and temperature of flow affect juvenile salmon by influencing travel-time, temperature-induced mortality and stress, and the timing of arrival at and the characteristics of the estuary and near-shore ocean environment. The importance of each of these characteristics in overall survival varies by species and between years.

Juvenile Migrant Travel Time vs. Flow and Spill

Yearling Migrants

A number of studies have found a positive relationship between migration rate of yearling chinook salmon and steelhead in the lower Snake and Columbia Rivers related to increases in flow (Raymond 1979, Berggren and Filardo 1993, Giorgi 1993, Cada et al. 1997).

Smith et al. (1999) analyzed the effects of flow and spill on the travel time and survival of PIT-tagged yearling chinook and steelhead released into the tailrace at Lower Granite Dam during the 1995 through 1998 migration seasons. In results presented below (and in the next section on survival), regression lines in figures are based on the model selection procedure detailed in Smith et al. (1999). In some cases, the data were not significantly different and a single regression line fit the combined data, in others where the data were significantly different, a separate regression line was selected for each year. For each fish detected at McNary Dam, the travel time from Lower Granite Dam tailrace to McNary Dam was calculated as the number of days between the time of release and the time of first detection at McNary Dam. Travel time included the time required for the smolt to move through four reservoirs and four dams (i.e., Little Goose, Lower Monumental, Ice Harbor, and McNary Dams). Travel time was regressed with flow (kcfs), percent of total flow that passed over spillways, and water temperature (C).

Measured conditions at Lower Monumental Dam were used as indices for the entire lower Snake River.

The correlation between flow exposure index and median yearling chinook salmon travel time was relatively strong and the linear regression lines appeared fairly consistent from year to year (Table 3, Fig. 3). The correlation between flow exposure index and median steelhead travel time was more variable than for yearling chinook salmon, however, linear regression lines appeared fairly consistent from year to year (Table 4, Fig. 4).

Although yearling chinook salmon and steelhead travel time was correlated with the percentage of water spilled, the relationships were not as consistently strong as with flow (Tables 3 and 4). When the spill exposure was less than 25%, particularly in 1995, travel time was more variable (Figs. 5 and 6).

Subyearling Migrants

Berggren and Filardo (1993) found a significant flow/travel time relationship for wild and hatchery subyearling chinook salmon in John Day reservoir (Lake Umatilla). Flow alone was significantly correlated ($P < 0.01$), but was a poor predictor of travel time ($r^2 = 0.28$). Inclusion of the range of flows encountered during migration and the serial date of entering the index reach improved the predictive capability of the model ($r^2 = 0.65$). The date at which salmon entered the reach was likely a function of fish development and smoltification.

A regression of travel time to flow for wild juvenile subyearling fall chinook salmon in the Lower Granite reservoir during 1991 and 1992 indicated that flow alone was a reasonable predictor of travel time ($r^2 = 0.53$ to 0.69) (Berggren 1994). The regression model's prediction was increased with the inclusion of smoltification-related variables ($r^2 = 0.79$ to 0.89). Berggren's regression equation predicted that at a given water temperature or photoperiod (increasing smoltification as the season progressed was associated with day length), fish greater than 85 mm migrated twice as fast at a flow of 50 kcfs than at a flow of 25 kcfs.

Muir et al. (1999) and recent unpublished NMFS analyses were conducted on PIT-tagged subyearling fall chinook salmon from Lyons Ferry Hatchery (Snake RKm 95) released at Asotin, Billy Creek, and Pittsburg Landing on the Snake River and Big Canyon Creek on the Clearwater River each week from late May to early July from 1995 through 1998. The number of groups and fish per group (Table 5) were considered sufficiently large to draw conclusions about travel time and survival from release to Lower Granite Dam. Indices of exposure to environmental factors were defined as the average daily value measured at Lower Granite Dam between the date of release and the date the 5th percentile passed Lower Granite Dam. Smith et al. (1997) and Muir et al. (1999) also conducted preliminary evaluations for the between Lower Granite and Lower Monumental Dams on groups of PIT-tagged fish redefined based on the date of Lower Granite Dam passage. The recent unpublished analyses by NMFS concluded that evaluations of effects on fish for this stretch of river was problematic and needs to await additional years of results. This conclusion was reached because too few groups existed in 1995 and 1996 and the

Table 3.   Summary of correlation and simple linear regression results for median travel time
(Lower Granite Dam to McNary Dam) of daily release groups of yearling chinook
salmon from Lower Granite Dam. (Based on Smith et al. 1999)

Exposure Index	Year	Linear regression			
		r^2	P value	intercept	slope
Flow	1995	64.04	<0.001	22.51	-0.096
	1996	65.30	<0.001	19.78	-0.066
	1997	64.68	<0.001	20.82	-0.061
	1998	66.75	<0.001	26.41	-0.102
	1995-1998	56.93	<0.001	21.41	-0.071
Spill %	1995	15.69	0.008	16.60	-0.199
	1996	53.11	<0.001	19.02	-0.237
	1997	61.63	<0.001	18.10	-0.226
	1998	26.90	<0.001	20.07	-0.232
	1995-1998	31.78	<0.001	17.82	-0.199
Temperature	1995	21.21	0.002	20.41	-0.665
	1996	10.79	0.044	18.82	-0.803
	1997	38.63	<0.001	28.01	-1.623
	1998	56.01	<0.001	63.38	-4.091
	1995-1998	3.35	0.017	17.36	-0.453
Release date	1995	55.59	<0.001	29.34	-0.134
	1996	1.47	0.468	14.14	-0.024
	1997	62.11	<0.001	26.10	-0.130
	1998	80.42	<0.001	44.86	-0.258
	1995-1998	50.94	<0.001	34.77	-0.184

Table 4. Summary of correlation and simple linear regression results for median travel time (Lower Granite Dam to McNary Dam) of daily release groups of steelhead from Lower Granite Dam.

Exposure Index	Year	Linear regression			
		r^2	P value	intercept	slope
Flow	1995	15.64	0.056	16.18	-0.045
	1996	51.55	0.000	16.05	-0.052
	1997	8.49	0.058	13.69	-0.031
	1998	68.41	0.000	20.44	-0.080
	1995-1998	54.73	0.000	17.35	-0.055
Spill %	1995	4.21	0.336	13.70	-0.114
	1996	74.19	0.000	18.16	-0.262
	1997	13.92	0.014	13.47	-0.148
	1998	32.87	0.000	15.93	-0.199
	1995-1998	43.04	0.000	15.82	-0.203
Temperature	1995	19.55	0.030	17.55	-0.557
	1996	7.72	0.169	17.94	-0.882
	1997	37.45	0.000	21.10	-1.196
	1998	52.09	0.000	48.81	-3.145
	1995-1998	6.42	0.002	16.17	-0.575
Release date	1995	56.35	0.000	26.23	-0.119
	1996	22.93	0.013	22.29	-0.104
	1997	49.74	0.000	20.68	-0.101
	1998	79.73	0.000	36.13	-0.209
	1995-1998	51.55	0.000	29.37	-0.159

Table 5. Data set used to study relationships of survival and travel time from release in the Snake and Clearwater Rivers to Lower Granite Dam with environmental factors for subyearling fall chinook salmon.

Year	Release dates	Number of groups	Range of release sizes	Total number of PIT-tagged fish
1995	31 May - 05 Jul	9	1,124-3,528	16,501
1996	06 Jun - 10 Jul	14	1,147-6,930	28,156
1997	03 Jun - 08 Jul	20	1,238-6,955	36,375
1998	02 Jun - 07 Jul	19	1,249-7,086	35,643
Total		62	1,124-7,086	116,675

Table 6. Data set used to study relationships of survival and travel time from Lower Granite Dam to Lower Monumental Dam with environmental factors for subyearling fall chinook salmon.

Year	Release dates	Number of groups	Range of release sizes	Total number of PIT-tagged fish

Weekly "release" groups from Lower Granite Dam

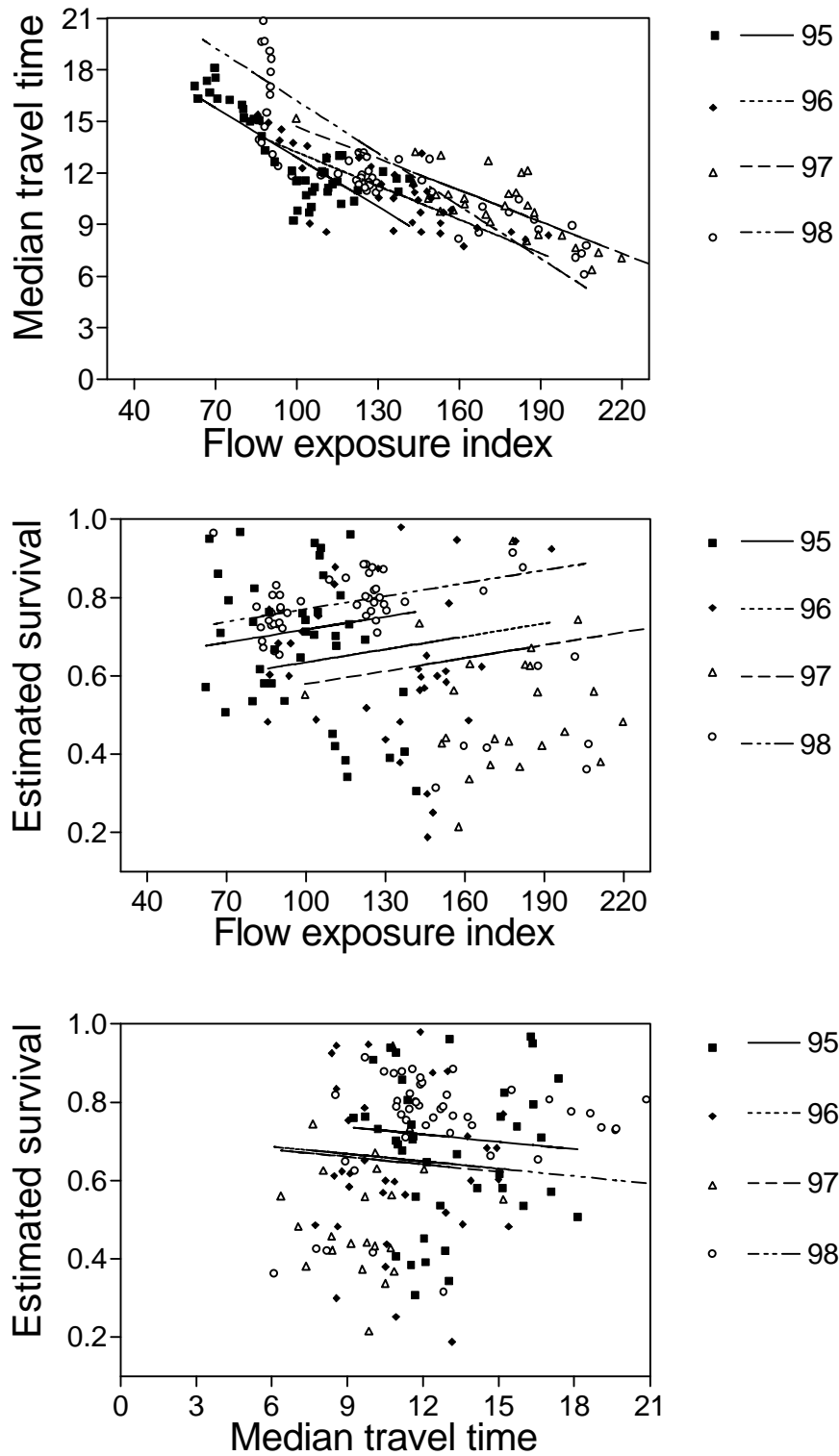| Year	Release dates	Number of groups	Range of release sizes	Total number of PIT-tagged fish
1995	11 Jul - 21 Aug	6	105 - 587	1,925
1996	06 Jul - 23 Aug	7	228 - 864	3,266
1997	09 Jun - 01 Sep	13	79 - 3,075	15,426
1998	23 May - 11 Sep	16	45 - 6,276	19,614
Total		42	45 - 6,276	40,231

Figure 3.   Relationships among median travel time (days) and estimated survival from Lower Granite Dam to McNary Dam, and flow exposure index (kcfs) measured at Lower Monumental Dam, yearling chinook salmon, 1995-1998.
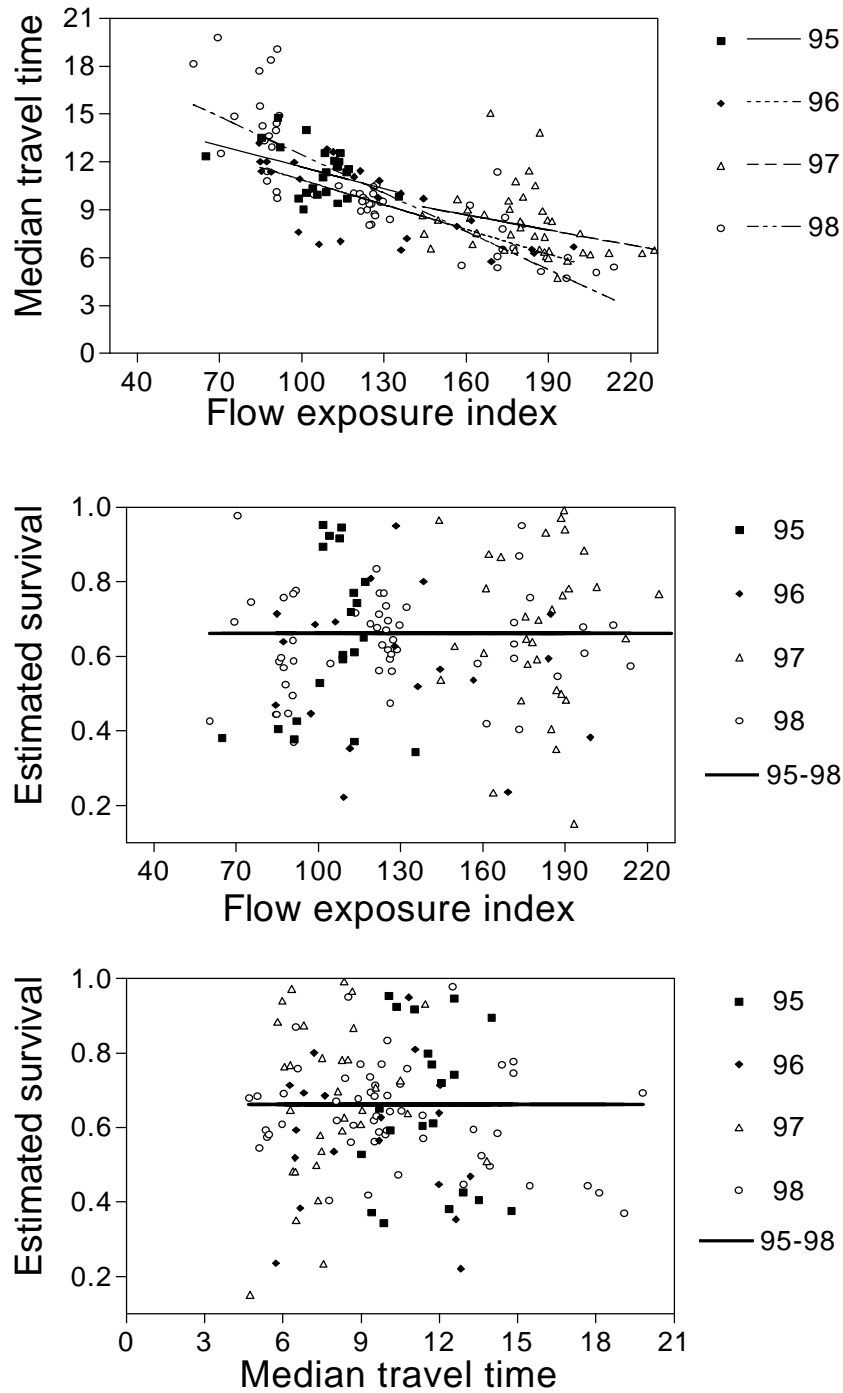
Figure 4. Relationships among median travel time (days) and estimated survival from Lower Granite Dam to McNary Dam, and flow exposure index (kcfs) measured at Lower Monumental Dam, steelhead, 1995-1998.
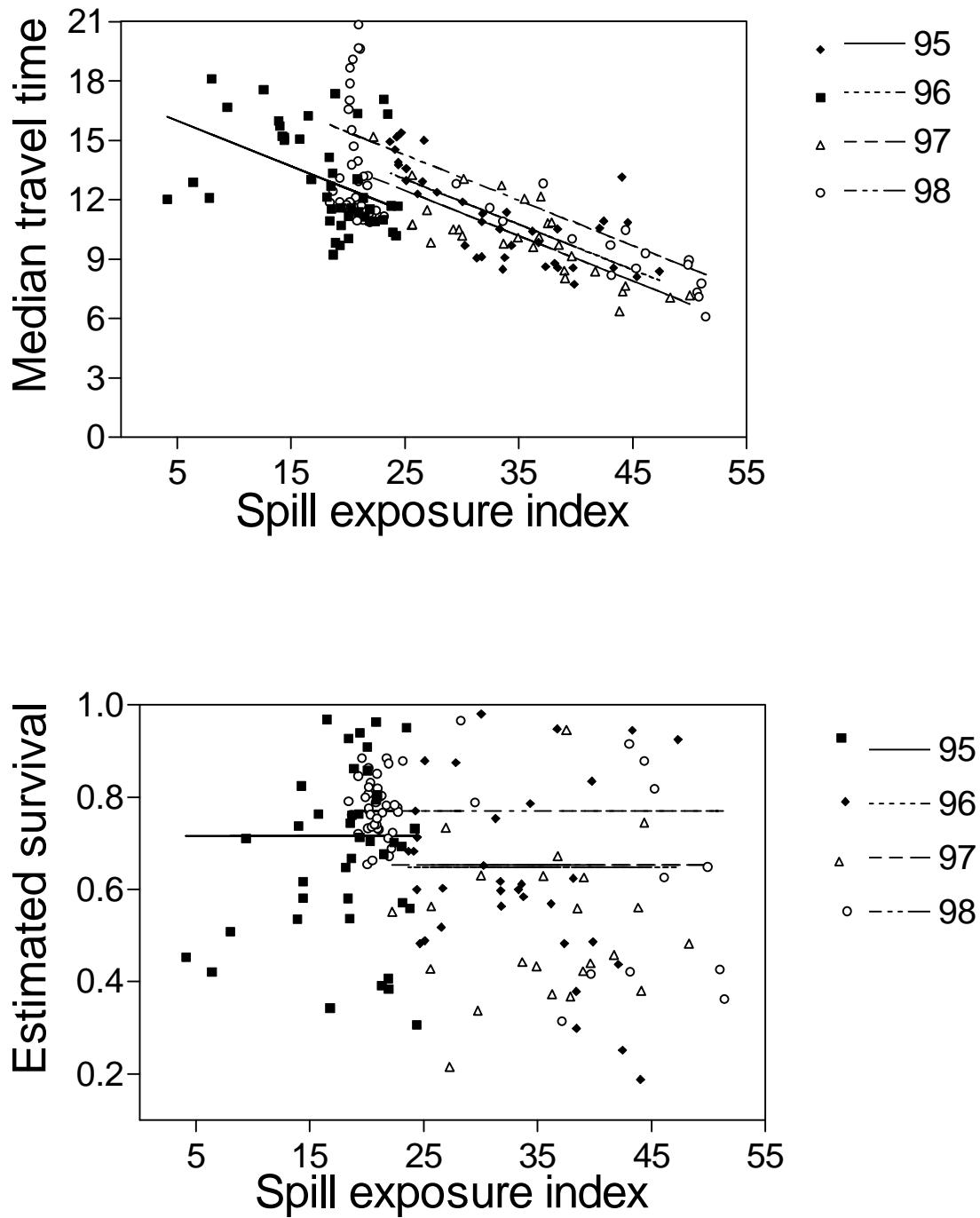
Figure 5. Relationships among median travel time (days) and estimated survival from Lower Granite Dam to McNary Dam, and spill exposure index (percentage of flow spilled) measured at Lower Monumental Dam, yearling chinook salmon, 1995-1998.
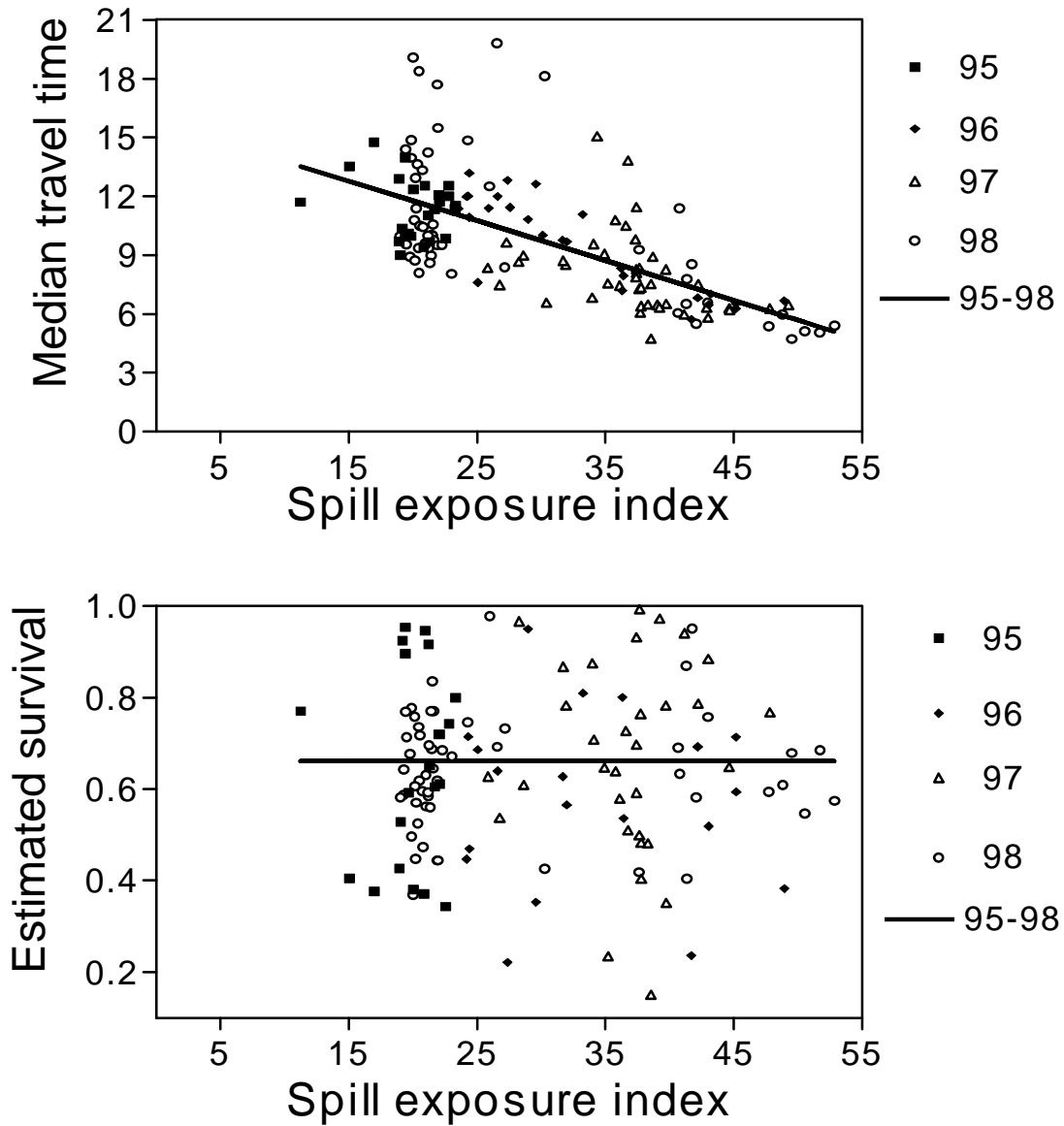
Figure 6.   Relationships among median travel time (days) and estimated survival from Lower Granite Dam to McNary Dam, and spill exposure index (percentage of flow spilled) measured at Lower Monumental Dam, steelhead, 1995-1998.

numbers of fish in many groups in 1997 and 1998 were too small (Table 6). Further, conditions varied little in 1995 and 1996, and conditions were quite anomalous in 1997 to all other recent years. Thus, discussions presented in this paper only reflect results from release in the Snake and Clearwater Rivers to Lower Granite Dam.

Relationships between median travel time and environmental variables from release to Lower Granite Dam were not clear (Figs. 7, 8, and 9, Table 7). Median travel time was significantly correlated with exposure indices in 1997, travel time increased as flow decreased, water temperature increased, and turbidity decreased (higher Secchi disk values represent clearer water). When the full range of flow was analyzed, a significant relationship between travel time and flow was not detected in other years; however, when only the data from conditions when flows were less than 100 kcfs were considered, a significant relationship between flow and travel time was also present in 1995 and the combined years of data indicated a nearly significant relationship between travel time and flow (Table 7).

Juvenile Migrant Survival vs. Flow and Spill

In the Snake River, Raymond (1979) and Sims and Ossiander (1981) found decreased survival for yearling chinook salmon under conditions of decreased flow (Fig. 10). There was great variability in the 1970s estimates of survival. Per-project survival estimates in the low-flow years of 1973 and 1977 were quite low, especially in 1973 when the estimated per-project survival was only 35%. From these studies and others conducted outside the Columbia Basin, Cada et al. (1997) surmised that a general relationship existed between increased downstream migrant fish survival within the hydropower system and increased river flow. The causative factors which may explain this relationship are poorly understood, and different factors are likely to dominate in different flow ranges and in different years and for different groups of fish (ISG 1996).

Changes in water velocity, spill, gas saturation, flooding, and temperature may relate to survival through fish migration speed, predation, route of passage at a dam, feeding, growth, and gas bubble trauma (ISG 1996). Increased travel time has led to later arrival of juvenile fall chinook salmon at dams when temperatures are higher, fish guidance into bypasses is decreased (Krcma et al. 1985; Monk et al. 1986; Gessel et al. 1991), and predation rates are higher (Beyer et al. 1988, Vigg 1988, Vigg and Burley 1991, and Vigg et al. 1991). With lower fish guidance, more fish pass through turbines, causing mortalities between 5 and 15% for subyearling fish (Holmes 1952, Ledgerwood et al. 1990). Additionally, since only guided fish are transported, they are the only ones that receive any benefit from transportation (Park 1985, Matthews et al. 1992). In addition to these mechanisms for which there is direct empirical evidence, indirect evidence suggests that predator efficiency is increased under conditions of low turbidity and higher water temperatures (increases predator metabolism) associated with low flows and the susceptibility to disease increases with water temperature (reviewed in CBFWA 1991).
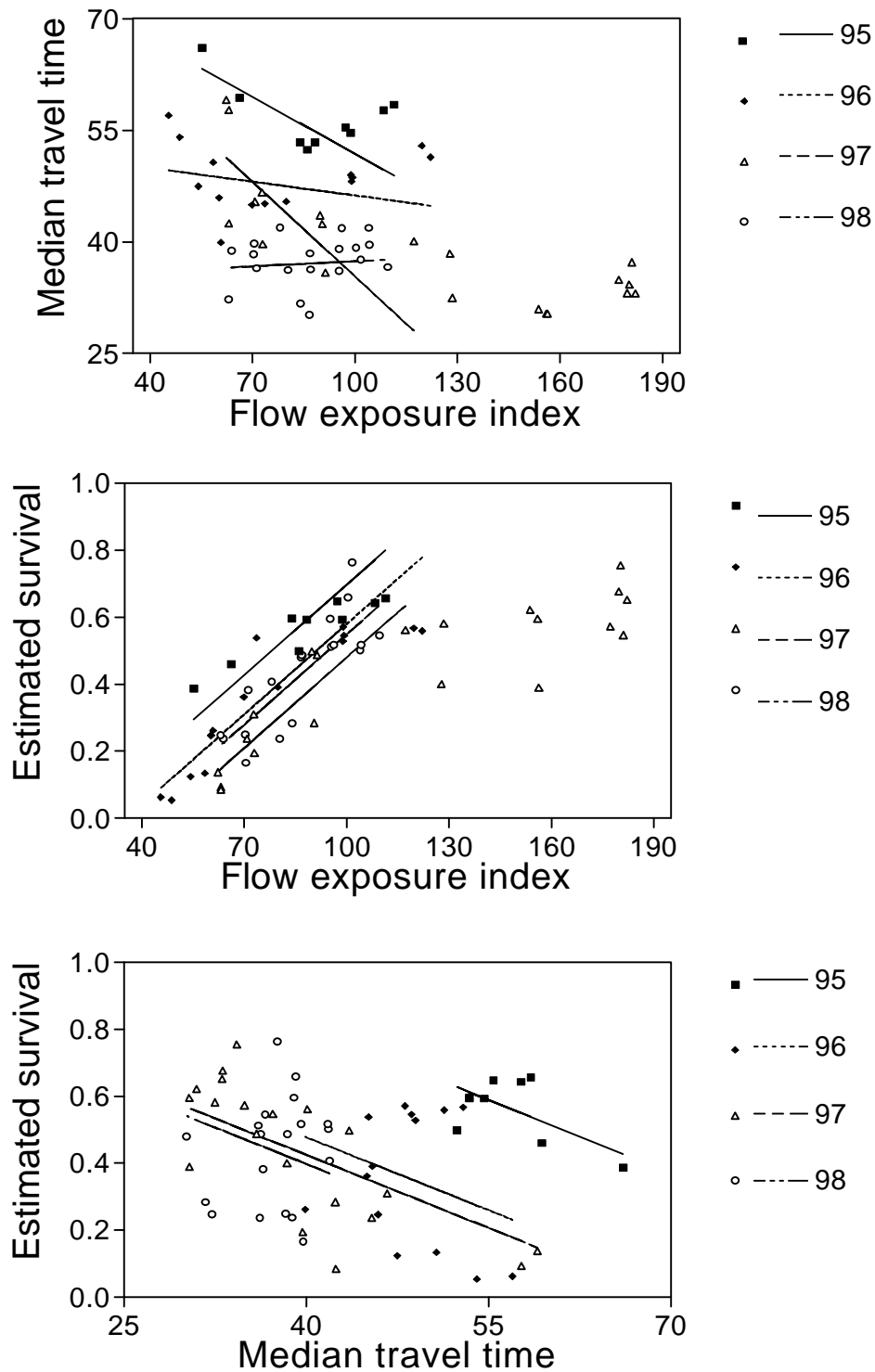
Figure 7. Median travel time (days) of subyearling chinook salmon from point of
release to Lower Granite Dam vs. mean daily flow (kcfs)measured at
Lower Granite Dam from release to 5 percent passage date at Lower
Granite Dam, and estimated survival vs. flow exposure and median
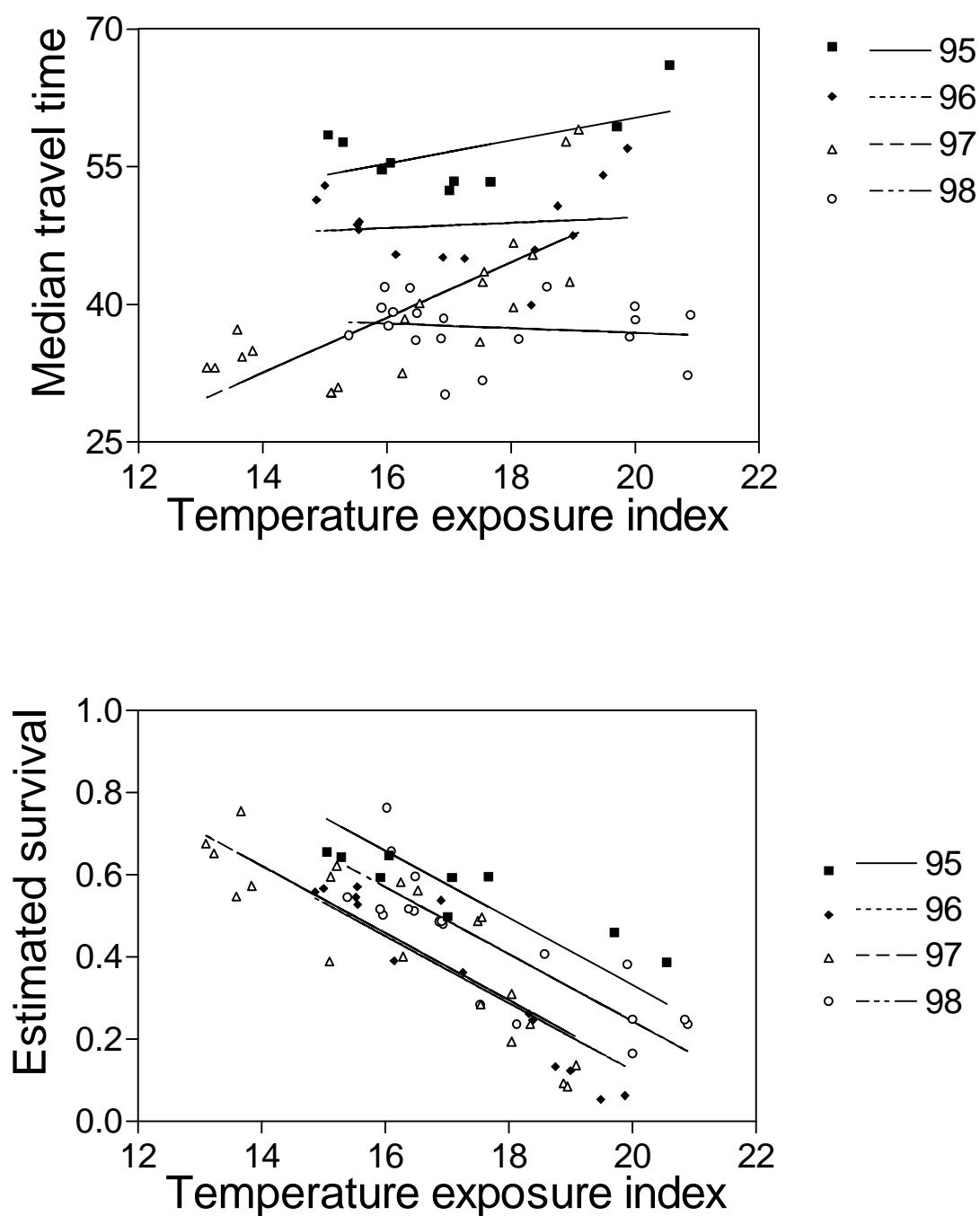travel time. Data from unpublished NMFS analyses.

Figure 8.   Median travel time (days) and survival of subyearling chinook salmonfrom point of release to Lower Granite Dam vs. mean daily water temperature (C) measured at Lower Granite Dam from release to 5 percent passage date at Lower Granite Dam, 1995-1998. Data from unpublished NMFS analyses.
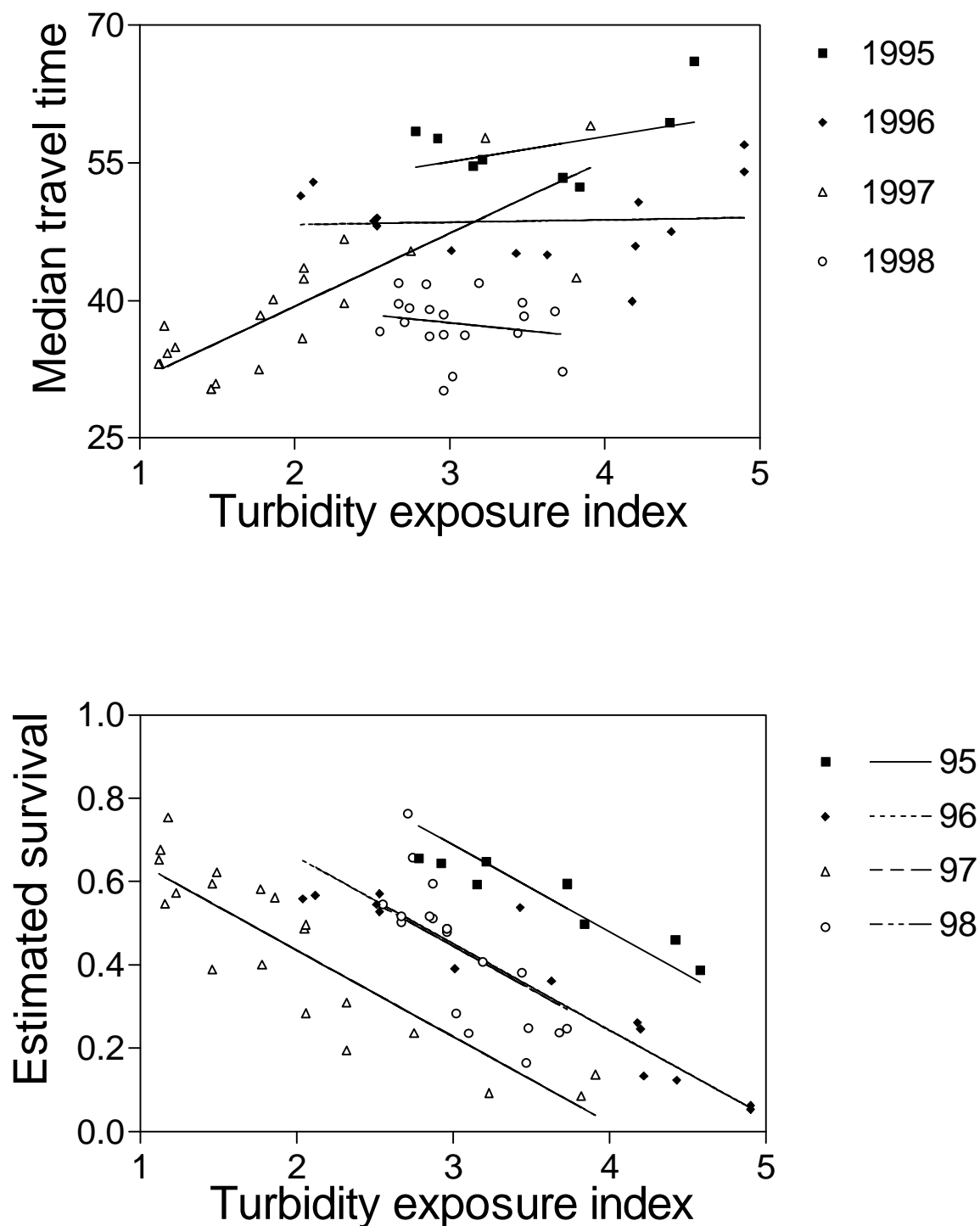
Figure 9. Median travel time (days) and survival of subyearling chinook salmon from
point of release to Lower Granite Dam vs. mean daily turbidity (Secchi disk)
measured at Lower Granite Dam from release to 5 percent passage date at
Lower Granite Dam, 1995-1998. Data from unpublished NMFS analyses.

Table 7. Summary of correlation and simple linear regression results for median travel time (days from release to Lower Granite Dam) of release groups of subyearling fall chinook salmon in Snake and Clearwater Rivers.

| Exposure Index	Year	R^2 (%)	P value	intercept	slope
		Linear regression			
Flow (full range)	1995	25.3	0.168	67.01	-0.116
(kcfs)	1996	0.4	0.837	47.80	0.010
	1997	59.5	<0.001	55.78	-0.136
	1998	5.5	0.332	32.79	0.054
	1995-1998	21.3	<0.001	54.63	-0.117
Temperature	1995	31.3	0.118	35.28	1.252
(°C)	1996	1.3	0.697	43.73	0.284
	1997	57.0	<0.001	-9.48	2.999
	1998	2.0	0.566	41.95	-0.254
	1995-1998	7.5	0.031	21.91	1.262
Turbidity	1995	16.6	0.276	46.89	2.744
(Secchi disk)	1996	0.4	0.840	47.72	0.257
	1997	68.1	<0.001	23.45	7.943
	1998	3.3	0.454	42.64	-1.698
	1995-1998	31.6	<0.001	28.57	5.137
Flow (<100 kcfs)	1995	70.7	0.018	77.30	-0.255
	1996	7.4	0.393	52.40	-0.062
	1997	44.5	0.050	77.69	-0.423
	1998	0.5	0.804	35.10	0.023
	1995-1998	6.6	0.099	56.25	-0.143
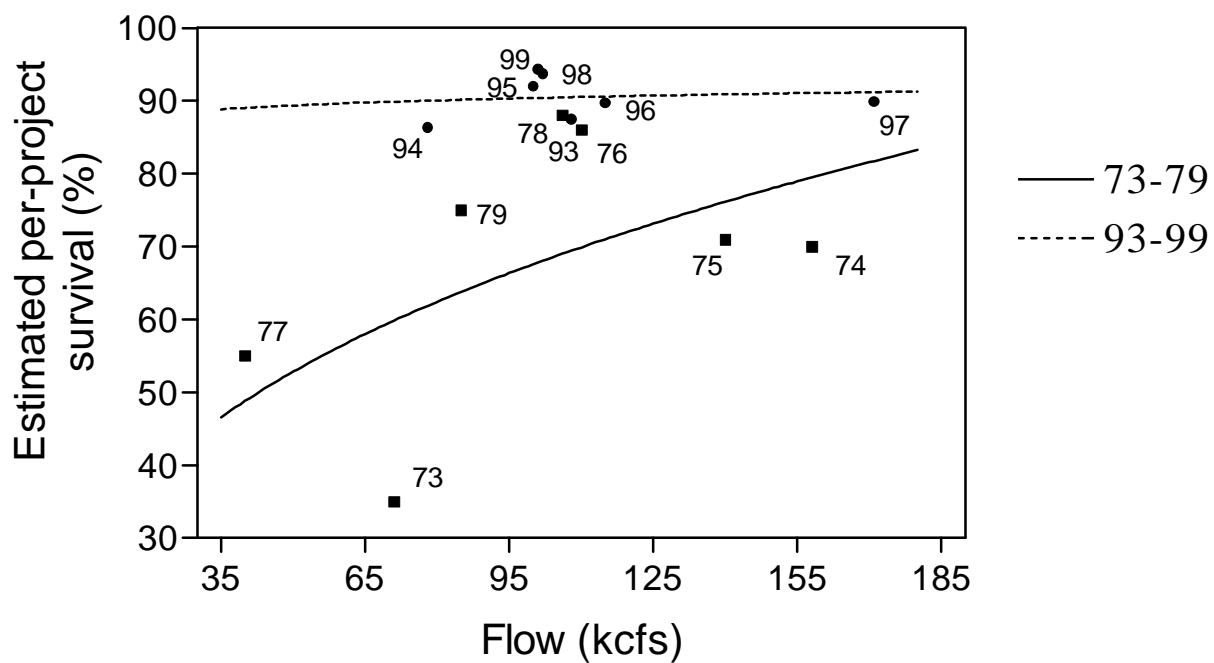
Figure 10. Historical and recent estimates of per-project survival (%) for yearling chinook salmon vs. index of Snake River flow (kcfs). Curves depict fitted nonlinear regression equations describing relationship between flow and survival in the two time-periods.

Yearling Migrants

From 1995 through 1998, survival probabilities were estimated for daily release groups from the Lower Granite Dam tailrace to McNary Dam tailrace (Smith et al. 1999). Survival was regressed with flow (kcfs), percent of total flow that passed over spillways, and water temperature (C). The measurement of each variable at Lower Monumental Dam was used as an index for the entire lower Snake River.

For yearling chinook salmon within individual years, the correlation of flow exposure and percentage of water spilled with estimated survival was weak and inconsistent from year to year (Figs. 3 and 5, Table 8). Within single years, the correlation was significant only with flow in 1998 (Table 8). Between estimated survival and travel time, there was a nearly significant $(P = 0.091)$ positive correlation (longer travel time, higher survival) in 1997 and a significant $(P = 0.036)$ negative correlation (longer travel time, lower survival) in 1998 (Fig. 3, Table 8). However, the r^2 was so low as to have almost no predictive value. No relationship was detected between per project survival and observed flow conditions (Fig. 10).

The correlation between steelhead survival estimates and flow and percentage of water spilled was also weak and inconsistent from year to year (Figs. 4 and 6, Table 9). The correlation was positive within some years and negative within others, but none of the correlations were significant (although in 1995 is was nearly so [$P = 0.078$]), but the range of observed exposures in that year was so narrow that the results did not appear reliable. Combining the points from all years resulted in r^2 of nearly zero between estimated survival and flow or spill exposure indices (Figs. 4 and 6, Table 9). For the range of variables measured, none of the independent variables (flow exposure, spill percent exposure, temperature exposure, travel time, or date of release) had any statistically detectable effect on estimated steelhead survival

Subyearling Migrants

Between release and detection at Lower Granite Dam, fish survival steadily decreased over time (Fig. 11), as flows and turbidity generally deceased and water temperatures increased (Fig. 12). The relationships between estimated survival from point of release to Lower Granite Dam tailrace and flow, temperature, and turbidity were strong and consistent for each year and for all years combined (Figs. 7, 8, and 9, Table 10).

Connor et al. (1998) found significant correlations between seasonal juvenile fall chinook salmon detection rates at Lower Granite Dam (roughly equivalent to minimum survival estimates) and both average seasonal flow and average seasonal water temperature. Connors et al. (1998) concluded that flow management that provides both flow augmentation and water temperature reduction is a beneficial interim recovery measure for enhancing survival of subyearling chinook salmon in the Snake River.

Table 8. Summary of correlation and simple linear regression results for estimated survival
(Lower Granite Dam to McNary Dam) of daily release groups of yearling chinook
salmon from Lower Granite Dam. (Based on Smith et al. 1999)

| Exposure Index | Year | Linear regression | | | |
		r^2	P value	intercept	slope
Flow	1995	0.09	0.850	0.680	0.0004
	1996	4.76	0.188	0.514	0.0012
	1997	0.19	0.822	0.768	-0.0007
	1998	8.60	0.025	0.656	0.0011
	1995-1998	1.61	0.100	0.691	0.0006
Spill %	1995	3.72	0.210	0.530	0.0097
	1996	3.13	0.288	0.515	0.0045
	1997	0.01	0.952	0.630	0.0007
	1998	2.13	0.274	0.846	-0.0036
	1995-1998	2.95	0.026	0.848	-0.0043
Temperature	1995	4.79	0.154	1.191	-0.0451
	1996	0.47	0.683	0.521	0.0135
	1997	7.85	0.141	2.124	-0.1354
	1998	9.54	0.018	0.444	0.0275
	1995-1998	10.40	<0.001	0.394	0.0313
Median travel time	1995	5.55	0.124	0.970	-0.0204
	1996	4.63	0.194	0.806	-0.0129
	1997	10.23	0.091	-0.043	0.0675
	1998	7.59	0.036	0.853	-0.0056
	1995-1998	1.46	0.118	0.810	-0.0036
Release date	1995	0.23	0.759	0.592	0.0010
	1996	0.00	0.997	0.646	0.0000
	1997	7.67	0.146	1.804	-0.0095
	1998	8.75	0.024	0.535	0.0021
	1995-1998	0.51	0.356	0.676	0.0007

Table 9. Summary of correlation and simple linear regression results for estimated survival (Lower Granite Dam to McNary Dam) of daily release groups of steelhead from Lower Granite Dam.

| Exposure Index	Year	Linear regression			
		r^2	P value	intercept	slope
Flow	1995	13.45	0.078	-0.138	0.0083
	1996	0.52	0.727	0.760	-0.0006
	1997	0.24	0.753	0.572	0.0009
	1998	0.17	0.765	0.669	-0.0002
	1995-1998	0.05	0.792	0.646	0.0001
Spill %	1995	5.07	0.290	0.015	0.0346
	1996	1.37	0.569	0.576	0.0034
	1997	0.83	0.561	0.527	0.0058
	1998	1.51	0.372	0.681	-0.0013
	1995-1998	0.00	0.988	0.662	0.0000
Temperature	1995	0.04	0.928	0.651	0.0081
	1996	2.09	0.481	0.188	0.0500
	1997	2.56	0.305	0.037	0.0654
	1998	4.23	0.132	0.169	0.0380
	1995-1998	0.23	0.563	0.750	-0.0072
Median travel time	1995	1.31	0.594	1.049	-0.0270
	1996	6.06	0.225	0.898	-0.0237
	1997	2.29	0.332	0.411	0.0399
	1998	0.05	0.870	0.658	-0.0011
	1995-1998	0.09	0.720	0.683	-0.0023
Release date	1995	4.86	0.301	-0.350	0.0089
	1996	0.24	0.810	0.489	0.0017
	1997	4.74	0.161	-0.264	0.0083
	1998	2.32	0.267	0.823	-0.0014
	1995-1998	0.40	0.443	0.784	-0.0010
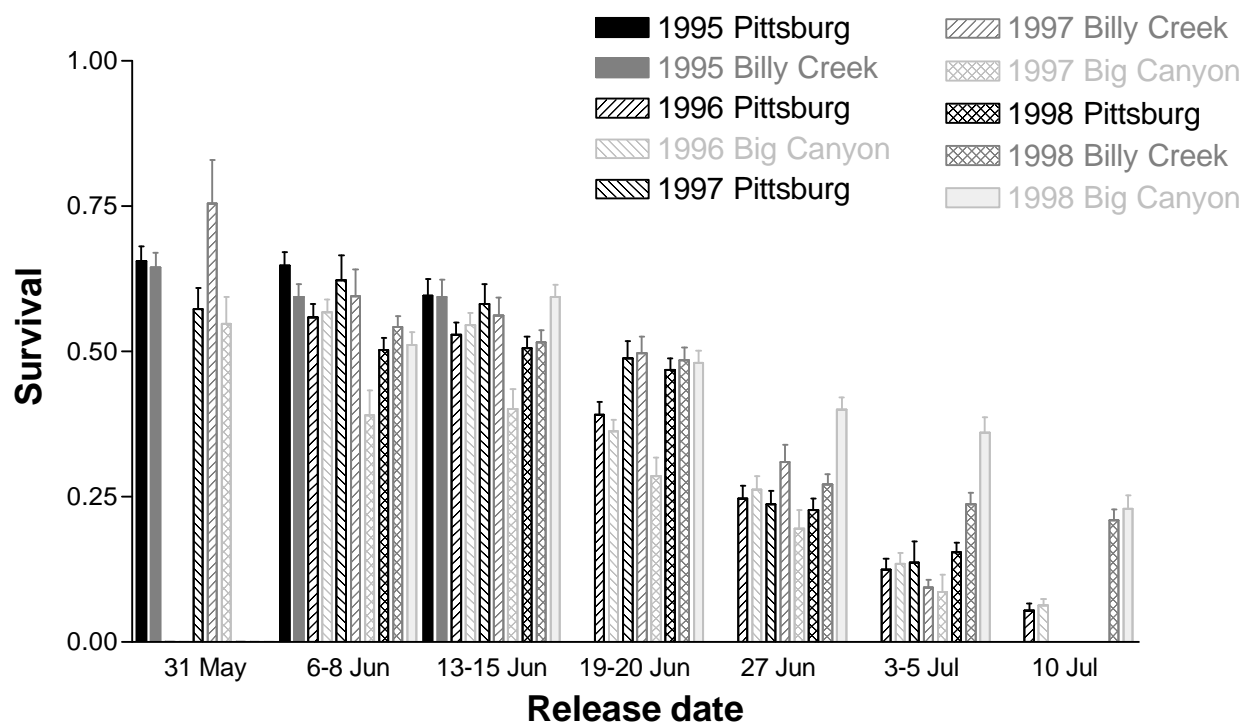
Figure 11. Estimated survival (with standard errors) of subyearling chinook salmon from point of release in the Snake (Pittsburg Landing and Billy Creek) and Clearwater (Big Canyon Creek) Rivers to the tailrace of Lower Granite Dam, 1995-1998.
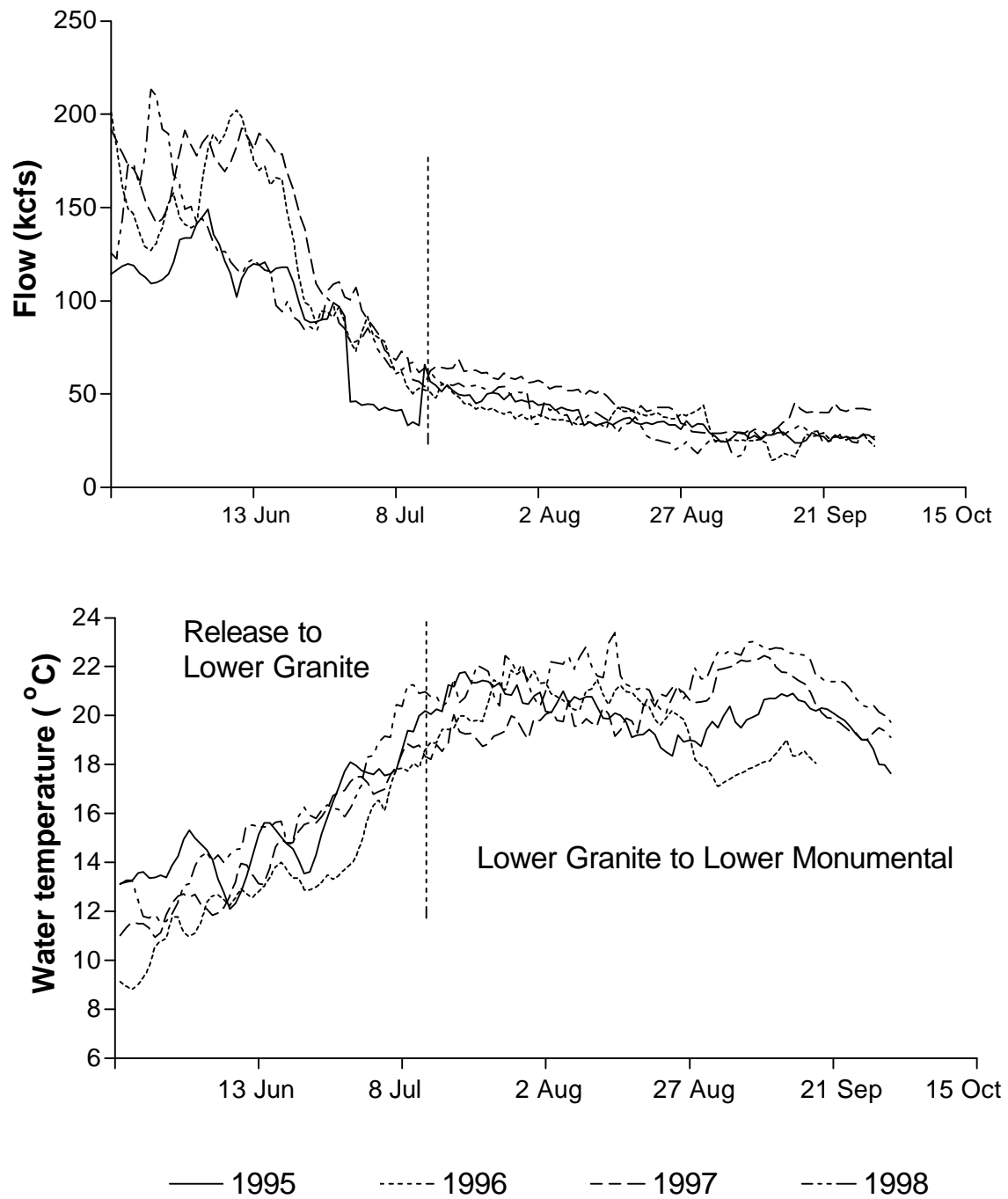
Figure 12. Environmental variables measured at Lower Granite Dam during the subyearling fall chinook salmon migration, 1995-1998. During the time period to the left of the dotted line, most subyearling fall chinook salmon are rearing and migrating to Lower Granite Dam while to the right, most are migrating through the hydropower system.

Table 10. Summary of correlation and simple linear regression results for estimated survival
probability (release to Lower Granite Dam) of release groups of subyearling fall
chinook salmon in Snake and Clearwater rivers. Data from unpublished NMFS
analyses.

		Linear regression			
Exposure Index	Year	R^2 (%)	P value	intercept	slope
Flow (full range)	1995	86.3	<0.001	0.147	0.005
(kcfs)	1996	81.2	<0.001	-0.200	0.007
	1997	74.3	<0.001	-0.028	0.004
	1998	68.8	<0.001	-0.374	0.009
	1995-1998	48.0	<0.001	0.081	0.004
Temperature	1995	83.9	0.001	1.340	-0.045
(^{o}C)	1996	92.2	<0.001	2.247	-0.110
	1997	74.5	<0.001	1.846	-0.087
	1998	68.3	<0.001	1.731	-0.073
	1995-1998	60.5	<0.001	1.715	-0.075
Turbidity	1995	85.7	<0.001	1.058	-0.137
(Secchi disk)	1996	89.6	<0.001	1.009	-0.189
	1997	78.8	<0.001	0.867	-0.216
	1998	65.4	<0.001	1.560	-0.369
	1995-1998	35.3	<0.001	0.764	-0.114
Median travel time	1995	30.9	0.120	1.260	-0.012
(Days)	1996	4.8	0.453	0.843	-0.010
	1997	58.8	<0.001	1.197	-0.019
	1998	4.0	0.410	0.066	0.010
	1995-1998	2.9	0.184	0.591	-0.004
Flow (<100 kcfs)	1995	83.5	0.004	0.104	0.005
	1996	86.8	<0.001	-0.345	0.009
	1997	79.1	0.001	-0.584	0.011
	1998	69.3	<0.001	-0.432	0.010
	1995-1998	68.1	<0.001	-0.367	0.009

Interpretation of Results

Identifying and quantifying relationships between environmental variables and travel times or survival of PIT-tagged migrant juvenile salmonid release groups in the Snake River present difficult challenges. Among these is defining the environmental conditions to which a release group is exposed. While operations to produce power have decreased the long-term flow variability inherent in the natural river flows of the Columbia and Snake Rivers, flows often vary widely over short times as generation is varied to match the electrical load demand. This occurs during the spring and during the summer. However, the percentage of change is likely higher during the summer when the base flow are much lower. For example, it is not uncommon for summer flows to vary as much as $\pm 40\%$ (e.g., 11.5 ± 4.5 kcfs) on a daily basis downstream from Hell's Canyon Dam. More sustained decreases in discharge also frequently occur over weekends as electrical demand declines. Because environmental conditions change over a short time relative to the time it takes for the bulk of a release group to migrate through a particular river section, the group is exposed to a range of environmental conditions. Further, fish from a single release group do not migrate as a group, but spread out over time. The problem is not too severe for yearling migrants. For example, in the spring, the average difference in travel time between the 10th and 90th percentiles for fish that passed between the tailrace of Lower Granite and McNary Dam was approximately 7 days. However, for example, fall chinook juveniles released into the Snake River at Billy Creek, just upstream from Lower Granite Reservoir, on 10 June 1997 were detected at Lower Granite Dam a median of 30 days later. However, individual fish were detected as early as 10 days and as late as 112 days after release (Muir et al. 1999). In this situation, estimated survival probabilities (determined post-season after all released fish have passed, died, or residualized) are valid estimates of average survival for the group; however, it is impossible to uniquely characterize the environmental conditions to which the entire release group was exposed.

Conversely, while flow conditions measured over a short time vary widely, efforts to meet the summer flow objectives on a weekly-average basis through flow augmentation cause weekly average flows to remain relatively constant throughout the summer season. This lack of variability reduces the range of conditions over which the dependent variables are measured, making it difficult to detect any relationships.

There are also important biological differences between study groups. Significant relationships have been detected between release date and travel time for yearling and subyearling chinook salmon and steelhead and have been hypothesized to relate strongly to the degree of smoltification (Berggren and Filardo 1993, Zabel et al. 1998). For yearling chinook salmon, the date of entry into a mid-Columbia index reach was strongly correlated with travel time, and was assumed related to higher flows and increased smoltification (Berggren and Filardo 1993). For subyearling chinook salmon, fish identified with longer travel times later in the season may have had lower levels of smoltification (Berggren and Filardo 1993).

Given these confounding effects, it is remarkable that survival and exposure indices have had any significant correlations.

Yearling Migrants

Despite a large database collected over several years using PIT-tagged fish and state-of-the-art analysis techniques, relationships between flow and survival and between travel time and survival through impounded sections of the lower Snake River were neither strong (within- or between-years) nor consistent from year to year. The relationships among travel time, survival, and environmental factors over the longest reach possible (Lower Granite Dam to McNary Dam), did not include 1993 and 1994 because the PIT tag interrogation system was not yet fully developed. During 1994, a spill program was implemented to improve the survival of yearling chinook salmon and steelhead, but not until 10 May after the majority of fish had passed (spill occurred at Little Goose Dam throughout the season due to a lack of generation capability). Consequently, the years with the lowest per-project survival and lowest spill percent exposure (1993 and 1994) were excluded. An analysis that included the 1994 migration (but only to the tailrace of Lower Monumental Dam) indicated that a significant relationship exists between spill percent and survival that was stronger than for flow in the combined year analysis (Smith et al. 1998). By maximizing the survival and travel time distance in an analysis of data from the 1995 through 1998 migration years (these years all had directed spill at dams as identified in the 1995 BiOp), the contrast in spill percent and survival was decreased, which may account for the lack of a significant relationship between the variables. In earlier studies, Sims and Ossiander (1981) found that spill had a more significant effect on survival than flow. Passing a higher proportion of smolts through spill decreases the number of fish passing through turbines, the dam passage route of greatest direct mortality.

Previous attempts to quantify the relationship between flow and survival for yearling chinook salmon (Raymond 1979, Sims and Ossiander 1981) have essentially correlated annual average survival with annual average flow (for year 10). The analyses of recent PIT-tag data show that patterns apparent in annual means (Fig. 10) are not present within a single migration season (Fig. 3, Table 5).

A strong and consistent relationship exists between flow and travel time. Increasing flow decreases travel time. Thus, although no relationship appears to exist within seasons between flow and yearling migrant survival through the impounded sections of the Snake River, by reducing travel times, higher flows may provide survival benefits in other portions of the salmonid life cycle and in free-flowing sections of the river both upstream and downstream from the hydropower system. For example, higher flows might improve conditions in the estuary (see above) and provide survival benefits to juvenile salmonids migrating through the estuary or the Columbia River plume (see below). By reducing the length of time the smolts are exposed to stressors in the reservoirs, higher flows also likely improve smolt condition upon arrival in the estuary.

Subyearling Migrants

Estimated survival probability from release points in the Snake River Basin to the tailrace of Lower Granite Dam was significantly correlated with flow and water temperature. Survival decreased markedly from early to late release dates. Since the environmental variables were also highly correlated with each other, determining which variable was most important to subyearling

fall chinook salmon survival is difficult. Therefore, fishery managers are presented with a complex problem when implementing summer flow management. For example, releases from Brownlee Reservoir increase flow through the free-flowing Snake River and Lower Granite Reservoir, but can cause deleterious water temperature increases in the late summer (Connor et al. 1998).

River flow, water temperature, and turbidity may affect survival for subyearling fall chinook salmon in a number of ways. Delays in passage may occur under lower flows for fish which migrate late in the season as compared to those that migrate early in the season. Hypothesized causes for such delays are disorientation of migrants, increased exposure time to predators, reversal of smoltification, and disease (Park 1969, Raymond 1988, Berggren and Filardo 1993). Lower flows also cause changes in operations at dams (e.g., less spill, greater diel-flow fluctuations) which can decrease fish survival. Warmer water for late season migrants leads to increased predation rates due to increased metabolic demands of predators (Curet 1993, Vigg and Burley 1991, Vigg et al. 1991). Fish guidance efficiency of turbine intake screens is also reduced in warmer water, resulting in more fish passing through turbines (Krcma et al. 1983), which may lead toward decreased survival. Vulnerability to sight-feeding predators may also increase as turbidity decreases (Zaret 1979) by increasing predator reactive distance and encounter rates (Vinyard and O'Brien 1976), as Shively et al. (1991) observed in Lower Granite Reservoir. Higher turbidity could reduce predation rates on juvenile salmonids by providing protective cover during rearing (Simenstad et al. 1982, Gregory 1993, Gregory and Levings 1998). Further, lower flows also cause changes in project operations that could affect dam passage.

Predator abundance and feeding selectivity, in concert with decreasing flow and increasing water temperature, may have caused the steady decline in survival probability estimates identified above for fish from different releases. Isaak and Bjornn (1996) found that peak abundance of northern pike minnow (*Ptychocheilus oregonensis*) in the tailrace of Lower Granite Dam occurred in July, during the subyearling fall chinook salmon migration. Poe et al. (1991) and Shively et al. (1996) found that predation rates depended on the size of juvenile salmonids, with smaller fish more vulnerable to predation. Fish size is one of the variables known to affect migration rates in fall chinook salmon, with smaller fish rearing longer in upstream areas before initiating migration (Connor et al. 1994). Thus, small subyearling fall chinook salmon that migrate late in the year may experience higher predation rates and lower survival as was reported for natural subyearling chinook salmon in the Clearwater River (Connor et al. 1997a,b). However, the low survival estimate (17% in 1995) may have resulted from unseasonably cold water releases from Dworshak Dam during the Clearwater River wild fall chinook salmon rearing period. Thus, summer flow augmentation to cool the Snake River in July and August may have adverse affects on wild fall chinook salmon growth and may delay or inhibit subyearling smolt development in the Clearwater River (Arnsberg and Statler 1995). Fisheries managers recognize this potential and delay releasing cool water from Dworshak Reservoir until the Clearwater subyearling chinook salmon reach an average size of 85 mm.

Estimated survival through reaches below Lower Granite Dam was lower in 1997 than in other years studied. This may have related to much higher flows observed in June and July of 1997 that resulted in fish migrating sooner in the year, and consequently arriving at the Snake

River dams at a substantially smaller size (from 30 to 40 mm smaller). The higher flows also increased the amount of debris at the Snake River dams, resulting in blockages within the bypass systems. In particular, blockages in the PIT-tag portions of the bypass systems required additional dewatering. Delayed mortality was higher for natural subyearling fall chinook salmon at Little Goose Dam during 1997 (7.7%) compared to 1995 (2.2%) and 1996 (1.4%), and higher than normal levels of columnaris infections were observed (Rex Baxter, COE, pers. commun., July 1999).

Relating travel time of actively migrating subyearling fall chinook salmon to environmental variables through reservoir reaches has proven difficult for researchers and has produced conflicting results (Berggren and Filardo 1993, Giorgi et al. 1994). Giorgi et al. (1997) found significant correlations between migration rate and flow, water temperature, date, and fish length (although low r^2 resulted in poor predictive capability) for PIT-tagged subyearling chinook salmon in the mid-Columbia River. Fish in this analysis were substantially smaller than migrant Snake River subyearling chinook salmon. Connor et al. (1998) found that the detection rate of PIT-tagged natural fall subyearling chinook salmon at Lower Granite Dam was significantly correlated with flow ($r^2 = 0.99$) and water temperature ($r^2 = 0.98$), similar to the results using Lyons Ferry Hatchery subyearling fall chinook salmon.

For Snake River subyearling chinook salmon significant correlations exist among survival, flow, water temperature, and turbidity. Survival was higher under conditions with higher flow, lower water temperatures, and higher turbidity. Obtaining additional years of data with variable environmental conditions will help define the relationships between survival of subyearling fall chinook salmon and travel time, flow, turbidity, and water temperature.

Smolt-to-Adult Returns (SAR)

Snake River Spring/Summer Chinook Salmon and Snake River Steelhead

Petrosky (1992) evaluated SARs from the upper Snake River dam until their return to that dam. He found a significant relationship between Raymond's (1988) 1964-1984 aggregate wild Snake River spring/summer chinook salmon and steelhead SARs compared to water particle travel time between Lewiston, Idaho, and Ice Harbor Dam ($r^2 = 0.66$, $P < 0.001$ and $r^2 = 0.48$, $P < 0.001$, respectively). Petrosky and Schaller (1998) updated the Snake River spring/summer chinook salmon SAR estimates to include the 1985-1994 migration years and adjusted the 1964-1984 estimates to remove harvest mortality and also found a significant relationships between water particle travel time in the Snake River and SAR (chinook salmon $r^2 = 0.54$, P not reported; steelhead $r^2 = 0.36$, P not reported) (Fig. 13). Significant relationships between water travel time and SAR were described for each species for the 1964-1994 migration seasons. In years with low water particle travel time (≤ 10 days), SAR was consistently high ($\geq 3\%$). With very high water particle travel time (≥ 27 days), SAR was consistently low ($< 2\%$).

Petrosky (1991) also estimated the ratio of spawner redd counts to redd counts of adults returning from the same brood year (recruits) for brood years 1975-1985 (migration years 1977-
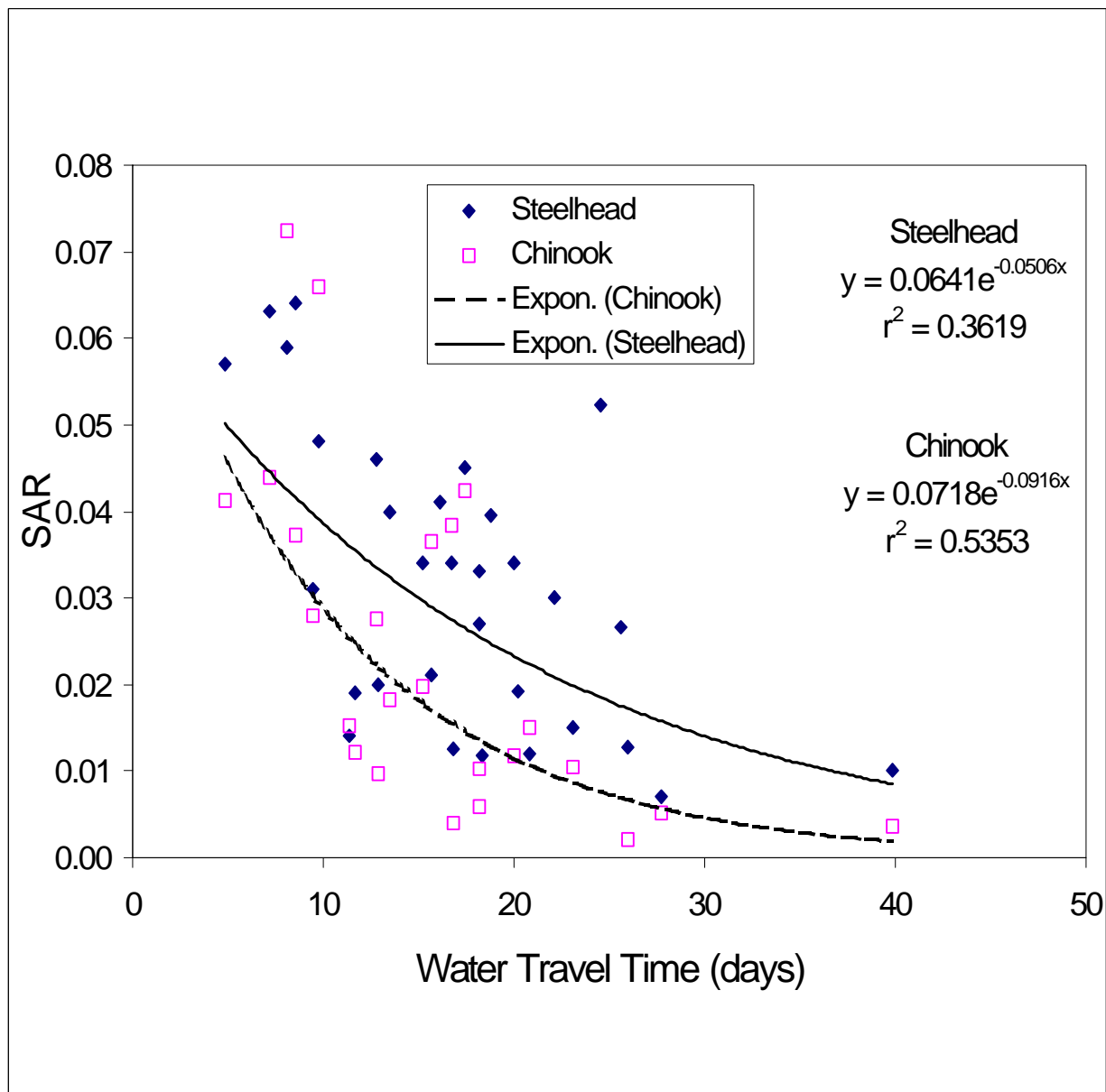
Figure 13. Regressions of Snake River wild steelhead and spring/summer chinook salmon smolt-to-adult returns (SAR) for 1964-1994 smolt migrations (after Petrosky and Schaller 1998).

1987). The recruit redds were estimated based on annual redd counts and average age of returning adults in the Middle Fork Salmon River. Because recruitment of salmonids is likely influenced by the number of spawners, both spawner-to-recruit survival and number of spawners (based on expanding redd counts by redds/female and mean sex ratios) were regressed against mean seasonal Snake River flow during the smolt migration year. In the resulting multiple regression, a significant ($P < 0.001$) positive coefficient was associated with flow. In the final model, which included both flow and spawner abundance, flow explained a large proportion of the variance ($r^2 = 0.78$ to 0.82, depending upon method of averaging flow). Petrosky (1992) updated the Marsh Creek analysis (Petrosky 1991) to include migration years 1960-1987. The results indicated a significant negative relationship between Marsh Creek SAR and mean seasonal water travel time from Lewiston to Ice Harbor Dam ($r^2 = 0.67$, $P < 0.001$).

Analyses by NMFS (unpublished) of adult returns from hatchery spring/summer chinook salmon PIT-tagged as juveniles at Lower Granite Dam in 1995 could not detect a relationship ($r^2 = 58.7$, $P = 0.13$ when data for flows > 130 kcfs were deleted [the last 6 days in May at the tail-end of the migration]) between SARs and flow in the Snake River when fish were grouped by
flow exposures over the outmigration period (Fig. 14). However, these results only represent one year of data. By fall 2001, 4 years of complete adults returns should provide enough additional data to determine if the lack of an in-season relationship holds.

Other researchers suggested that increased adult salmon returns occurred following high flow years (Smoker 1955, Scarnecchia 1981). Yearling chinook salmon and steelhead have evolved to migrate during the spring, suggesting that over the evolutionary time scale, spring conditions, including higher river flows, provide an adaptive advantage for survival. Furthermore, variable flows are a natural part of river ecology, benefitting other riverine processes (Stanford et al. 1996, ISG 1996).

Upper Columbia River Steelhead

Raymond (1988) estimated wild steelhead SARs for fish passing Priest Rapids Dam from 1962 to 1984. Cooney (1998) updated these estimates through 1994 and adjusted both the Raymond (1988) and newer estimates to remove the mortality associated with harvest. Although there is a significant relationship between these harvest-adjusted SAR estimates and mean April 15 - May 31 flow (Fig. 15), the r^2 has little predictive value. At seasonal average flows below approximately 125 kcfs and above approximately 180 kcfs, SARs were consistently less than 2%. At intermediate flows, SAR estimates above 2% were observed. Data for hatchery steelhead returning to Priest Rapids Dam (Brown 1995, Raymond 1988) and Wells Dam (Mullan et al. 1992) showed that below average period flows of 125-140 kcfs SARs were almost always less than 2%. At higher flows, SARs ranged from 1 to 7%, generally greater than 1.5% (NMFS 1998).
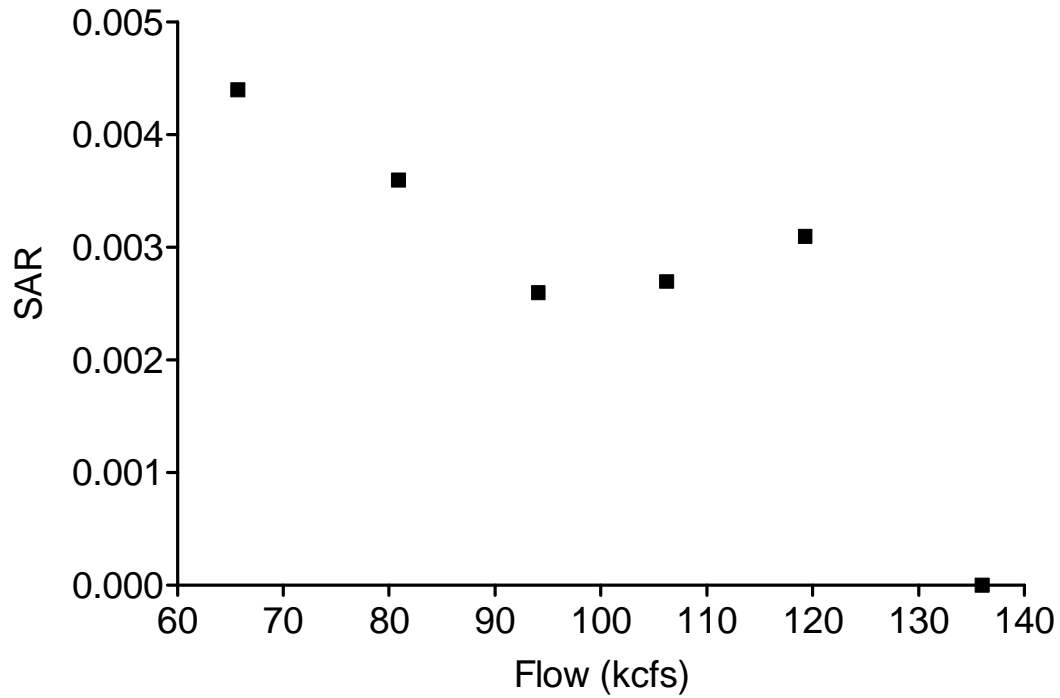
Figure 14. Smolt-to-adult return (SAR) to Lower Granite Dam for hatchery
spring/summer chinook salmon PIT-tagged and released into the tailrace
of Lower Granite Dam as part of NMFS transportation studies in 1995.
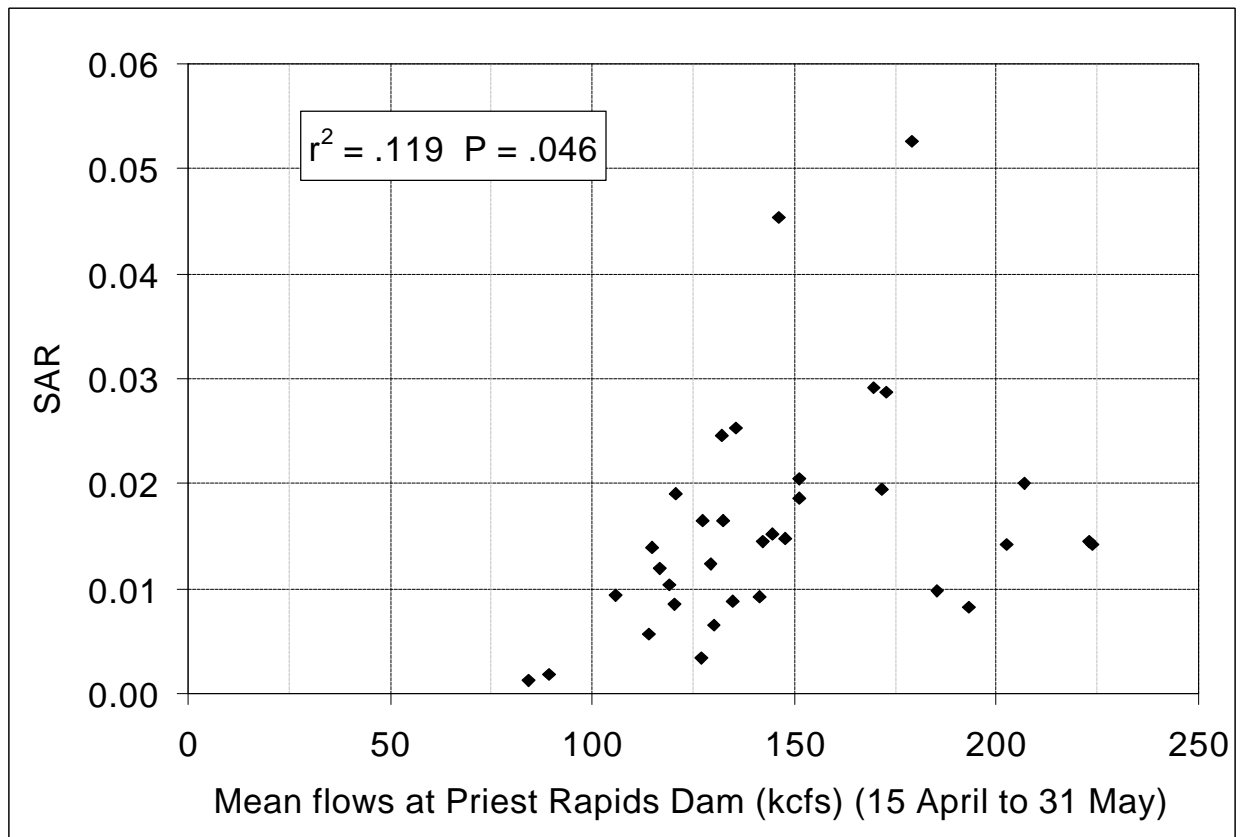Data from unpublished NMFS analyses.

Figure 15. Estimated smolt-to-adult returns (SAR), adjusted for harvest rate, for wild upper Columbia River steelhead from 1962-1995 smolt migrations.

Subyearling Chinook Salmon

Giorgi et al. (1994) found that subyearling chinook salmon migrating through the John Day reservoir early in the summer contributed more adults than juveniles migrating later in the summer for all three years of the study (1981-83). Early fish migrated under conditions of higher flows, lower water temperatures, and lower predation rates. Recoveries of greater than 1% did not occur at less than 200 kcfs and the highest recoveries occurred with average flows greater than 200 kcfs (Fig. 16).

Hilborn et al. (1993) found a significant relationship between flow and adult returns of Priest Rapids fall chinook salmon. However, Skalski et al. (1996), in further analysis, concluded that it was not possible to determine the key factors that influenced these hatchery return rates with the available data and statistical techniques.

Interpretation of Results

While the data consistency show that high water particle travel times (low flows) during the yearling salmon outmigration season are followed by low SARs, in analyses that covered a number of years (e.g. Petrosky 1992), considerable differences often existed in the configuration or operation of the hydropower system between years. In analyses based on Raymond's adult returns, five of the six highest SARs occurred prior to construction of the upper three dams on the Snake River and John Day Dam on the lower Columbia River. Prior to construction of these, dams there were not only shorter water particle travel times (due to fewer reservoirs) but fewer dams to pass. Because dam passage imposes additional sources of mortality, it is inappropriate to attribute the higher SARs in these years to shorter travel times alone. The higher SARs observed in those years may have resulted from either factor or both. If the data points from the period prior to construction of the last four dams are removed (pre-1975), the relationship between travel time and adult returns is weak and fairly flat suggesting that migration season water particle travel time is a poor predictor of SAR.

Some analyses have indicated that a minimum flow in the impounded hydropower system is required for successful adult returns. Petrosky (1991) found that Snake River spring/summer chinook salmon SARs were always low (below approximately 0.1%) when mean Snake River flows were below 85 kcfs during the spring migration (April 20-May 31) and that SARs increased as water particle travel time decreased (Petrosky 1992). When average period flows were above 85 kcfs, SARs were often higher (up to 1.6%). Mundy et al. (1994) also found that low flow conditions in the hydropower system during the juvenile outmigration resulted in low adult returns of Snake River fish. Upper Columbia River steelhead also had low SARs under low flows, but both high and low SARs were observed at higher flows.

However, a number of improvements in the hydropower system over the last 20 years have led to increases in survival of Snake River yearling chinook salmon such that they are now as high with eight dams in place as they were historically when only four dams were in place (Fig. 17). Nonetheless, SARs in recent years have remained low, making it clear that many
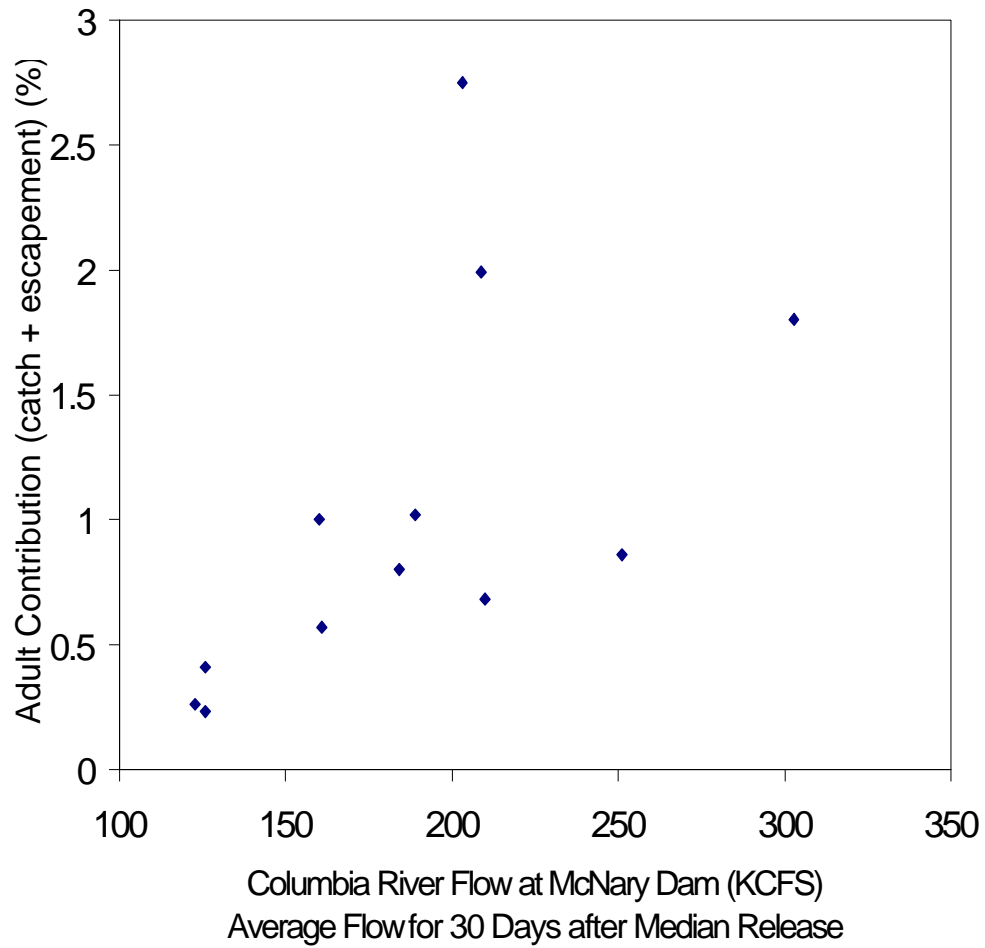
Figure 16. Adult contributions vs. flow at McNary Dam for subyearling chinook salmon outmigrating in 1981, 1982, and 1983 (from Giorgi et al. 1994).
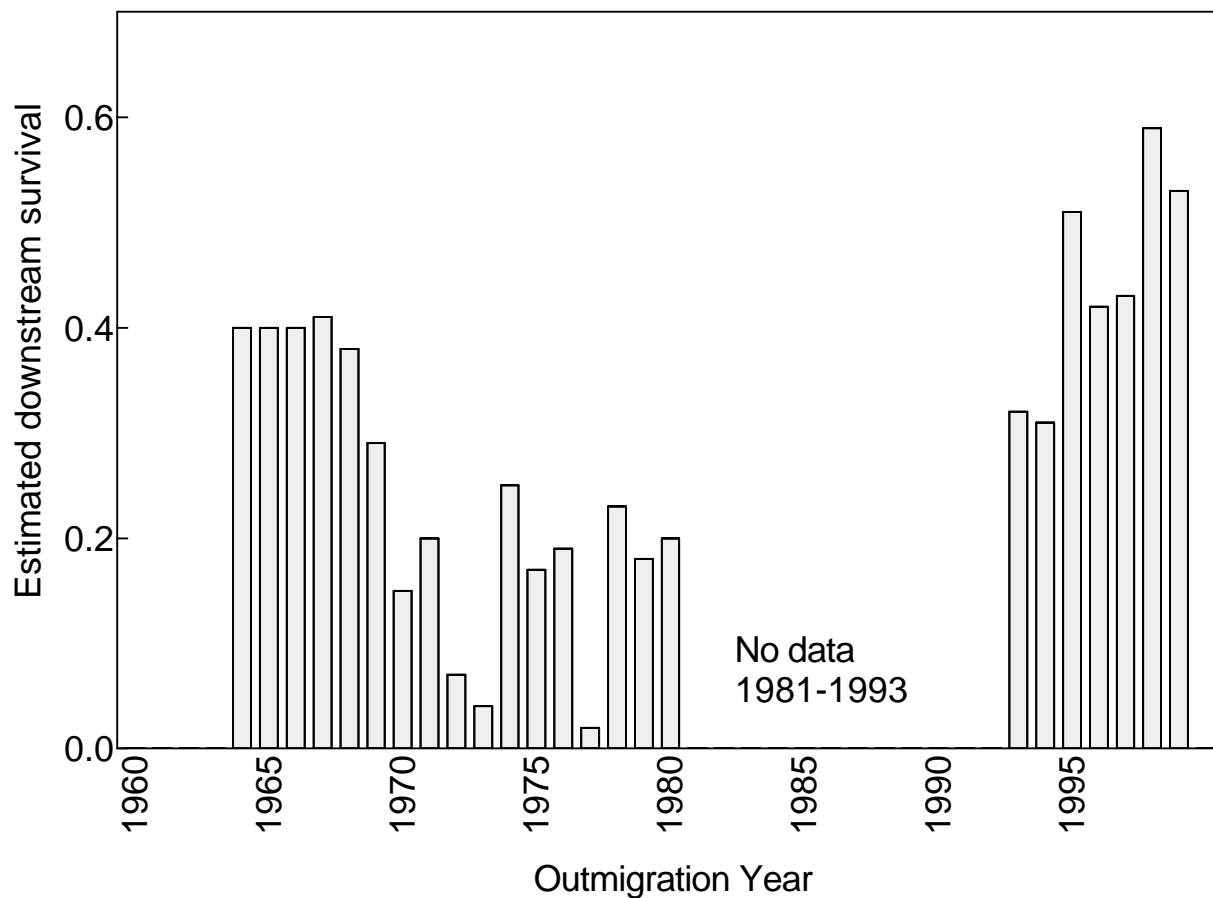
Figure 17. Estimated survival (estimates based on extrapolations outside of reaches actually measured) of juvenile spring/summer chinook salmon from the upper dam on the Snake River to the tailrace of Bonneville Dam. From 1964 to 1967 juveniles passed Ice Harbor, McNary, The Dalles, and Bonneville Dams. Additional dams were added in 1968 (John Day Dam), 1969 (Lower Monumental Dam), 1970 (Little Goose Dam), and 1975 (Lower Granite Dam). Data from unpublished NMFS analyses.

factors other than passage through the hydropower system affect the probability that downstream migrant juveniles will survive to return as adults. Other factors include estuarine and ocean survival, adult upstream passage survival, and in-river harvest. Additionally, since a high proportion of smolts have been transported from the upper Snake River dams to below Bonneville Dam since 1977, an association between SAR and flow for Snake River migrants must reflect either delayed effects of flow conditions experienced upstream from transportation sites or flow conditions experienced in the estuary or Columbia River plume after barge release. However, upper Columbia River spring chinook salmon SARs from the juvenile outmigrations from 1964 to 1984 showed the same trends as those from the Snake River (Raymond 1988), even though the percentage of the juvenile outmigration that was transported from McNary Dam was considerably less than that transported out of the Snake River.

Although the flow/SAR relationship is difficult to interpret and may not relate entirely to improved survival through the hydropower system, the data indicate an adult return benefit from higher outmigration flows.

Effects on Juvenile Migrant Survival in the Estuary and Near-Shore Environment

The Columbia River plume is a freshwater/seawater interface that provides critical habitat for juvenile salmon survival. The mechanisms by which the Columbia River estuary and plume affect juvenile salmon survival have not been quantified, but likely include provision of food and refuge during transport away from coastal predation. The shape of the Columbia River plume is affected by ocean currents and by the amount of fresh water flowing out of the Columbia River. In addition to flow, the amount of sediment affecting turbidity and the amount of nutrients and organic inputs fueling estuarine and oceanic productivity are likely important to salmon growth and survival.

Water developments in the Columbia River have reduced average flow and altered the seasonality of Columbia River flows and sediment discharge, and have changed the estuarine ecosystem (NRC 1996; Sherwood et al. 1990; Simenstad et al. 1990, 1992; Weitkamp et al. 1994). Annual spring freshet flows (May and June) through the Columbia River estuary are about 70% of pre-development levels, and total sediment discharge is about one-third of 19th-century levels.

Decreased spring flows and sediment discharges have also reduced the extent, speed of movement, thickness, and turbidity of the plume that extended far out and south into the Pacific Ocean during the spring and summer (Barnes et al. 1972, Cudaback and Jay 1996, Hickey et al. 1998). Pearcy (1992) suggested that low river inflow is unfavorable for juvenile salmonid survival despite some availability of nutrients from upwelling, because of: reduced turbidity in the plume (increasing foraging efficiency of birds and fish predators); increased residence time of the fish in the estuary and near the coast where predation is high; decreased incidence of fronts with concentrated food resources for juvenile salmonids; and reduced overall total secondary productivity based on upwelled and fluvial nutrients. Reduced secondary productivity affects not only salmonid food sources but focuses predation by other fishes and birds on the juvenile salmonids.

Finally, due to decreased river flows and development of the hydropower system, most migrant salmon likely arrive in the estuary later than under conditions in which they evolved. Efforts to restore the Columbia River plume toward conditions that existed prior to development of the hydropower system would likely benefit salmonids (ISG 1996).

EFFECTS OF FLOW ON ADULT FISH PASSAGE

Adults of all Snake and middle and upper Columbia River salmon species listed under the ESA migrate upstream through the hydropower system during flow management periods. Spring and summer chinook salmon migrate from late March through July; sockeye salmon migrate in June and July; fall chinook salmon migrate from late August through October. Steelhead (all are summer run) migrate from June through October at Bonneville Dam and during the same year from September through November at Lower Granite Dam. In November when water temperatures become quite cold, adult steelhead stop migrating until March through May of the following year (COE 1998).

High spill at dams substantially delays passage of adult chinook salmon (Turner et al. 1983; Turner et al. 1984; Bjornn and Peery 1992). Such spills are involuntary as they result from high flows that considerably exceed powerhouse capacities. Present spring flow objectives in the Snake and Columbia Rivers are at levels (spring: 85-100 kcfs in the Snake, 135 kcfs in the mid-Columbia and 220-260 kcfs in the lower Columbia) that generally do not cause spill at mainstem dams because powerhouse capacities exceed flow objectives. (The one exception is at McNary Dam, where powerhouse capacity is 85 to 90 kcfs less than the flow objectives in spring and summer. Note: the voluntary spring spill program provides spill at higher levels [120-140 kcfs] at McNary than would occur due to flow augmentation [85-90 kcfs]). Thus, flow augmentation does not cause high levels of spill at these projects and, therefore, does not cause adult passage delays associated with high spills.   When turbine outages occur, flow management to meet the flow objectives may result in flow that exceeds powerhouse capacities, resulting in spill. This rarely occurs. During the summer, lower flows and lower flow objectives (50-55 kcfs in the Snake, 200 kcfs in the lower Columbia) result in little or no spill, thus summer flow management does not affect adult passage.

Temperature is an important environmental condition influencing the survival of upstream migrant salmon (Coutant 1970). High temperatures delay entry of salmon and steelhead into the lower Snake River (Stuehrenberg et al. 1978). Maintaining Snake River water temperatures to below 21 C would reduce risk to populations of migrating adult salmon (Dauble and Mueller 1993). Cool water releases from Dworshak Dam have a cooling effect throughout the lower Snake River (Karr et al. 1998). Temperature reductions at Lower Granite Reservoir are strong and almost immediate following release from Dworshak Dam and have lesser affect and occur later at each downstream reservoir (Karr et al. 1998). This thermal inertia also causes the cool water to persist downstream well after releases are discontinued. For example, while Dworshak releases began on July 5, 1994, the greatest temperature reduction did not occur at Ice Harbor Reservoir until August 13, almost two weeks after Dworshak releases were discontinued. Temperatures reduction continued for several more weeks and remained below 21 C throughout

the adult migration season. Thus, temperature control primarily aimed at improving conditions for downstream migrant juvenile fall chinook also benefits adult steelhead and fall chinook salmon in the river in late August and September.

SUMMARY AND MANAGEMENT IMPLICATIONS

Flow/Travel Time

Recent and past research demonstrates there is a strong flow/travel-time relationship for yearling chinook salmon and steelhead and a lesser relationship for subyearling chinook salmon that migrate in the summer. Correlations are stronger for spring than summer migrants. Travel time of yearling chinook salmon and steelhead tends to decline with date with increases in flow and the degree of smoltification. However, subyearling fall chinook exhibit more complex behaviors, as they migrate slowly if at all at body lengths less than about 80 mm and may slow or stop migrating later in the migration season when flows decrease and water temperatures increase.

Fall chinook salmon juveniles from the Hell's Canyon section of the Snake River currently migrate downstream 4 to 6 weeks later than they did prior to development of the basin's water resources (Kcrma and Raleigh 1970, University of Washington, DART data-base, 1996 - 1999), placing them at the lower Snake River dams during naturally low flow and warm water conditions. This is likely a result of changes in the thermal regime downstream from Hell's Canyon Dam as water temperatures are now warmer in the fall and cooler in the spring. This delays adult spawning in the fall and emergence and fish growth in the spring. If modifications to Brownlee Dam were possible to change the temperature of the outflow from the dam to approximate more closely historic conditions, spawning, emergence, and rearing of fall chinook salmon might lead to more historical outmigration timing. Such changes in outmigration timing might substantially improve survival of Snake River juvenile fall chinook salmon as they would likely migrate downstream under much more favorable flow and water temperature conditions.

Flow/Survival

Recent research has not demonstrated a flow/survival relationship for spring migrants through specific reaches of the lower Snake River. However, consistent and highly significant relationships have been observed between flow and survival for juvenile fall chinook (summer migrants) from release points in the free-flowing portion of the Snake River to Lower Granite Dam. The fact that temperature and turbidity are also correlated with survival requires managers to consider both quality and quantity factors when managing flows to benefit this population. Further, although no direct juvenile fish survival benefits were detected through specific reaches of the hydropower system under the good flow and spill conditions that have existed since the implementation of the 1995 BiOp, flows may provide survival benefits downstream from the hydropower system for fish as they migrate through the estuary and into the near-shore ocean environment.

Smolt-to-Adult Returns

Analysis of smolt-to-adult (SAR) returns indicates a relationship between flows and year-class success. The SARs of yearling and subyearling chinook salmon and steelhead are always low when mean Snake River, upper (mid-) and lower Columbia River flows during the outmigration periods for these fish are below 85, 135, and 200 kcfs, respectively. These results support management actions to provide flows of at least 85 kcfs in the Snake River and 135 kcfs in the upper (mid-) Columbia River during the spring and 200 kcfs in the lower Columbia River during the summer.

The Estuary and Near-Shore Environment

The development of the hydropower system has had a significant effect on the volume and timing of water entering the Columbia River estuary. The fact that the hydropower system has also significantly altered the timing of juvenile migrants arriving at the estuary supports the need to manage flows in the Columbia River toward a more natural spring hydrograph.

Flow Management

Flow management for the Snake and Columbia Rivers appears to provide salmon survival benefits. However, the benefits are difficult and somewhat speculative to quantify and are not easily demonstrated for every population at all times. The Appendix presents rough estimates of the benefits of flow management on Snake River fall chinook during selected recent years.

Research conducted since 1995 suggested that the spring flow objectives (Table 2) for the Columbia River are reasonable. They do not provide historical flows or provide conditions that will move juvenile migrants through the area of the hydropower system to the lower river and estuary that matches historical timing. The impoundments create delays which flow management cannot entirely overcome. However, of the spring/summer chinook salmon juvenile population that migrates downstream through the hydropower system has survival rates that approach levels measured in the 1960s (Fig. 17). This does not imply that smolt survival levels are high enough to ensure recovery for the species, nor does it suggest that flow management is the primary causative agent for this improvement. Rather it suggests that flow management, in conjunction with other fish protection measures, has had a beneficial effect on smolt survival.

Direct evidence for a survival benefit to fall chinook from flow management is strongly supported by research results. Data sets consistently demonstrated strong relationships between flow and survival, and temperature and survival. The provision of suitable environmental conditions would likely provide substantial survival benefits. Both Snake River fall chinook travel time and survival are improved by increasing flows (Muir 1999). The data indicate that benefits of additional flow continue at flows well above those recently observed during a wetter than average hydrologic condition which included the use of stored water to augment flows. The ability to increase flow augmentation substantially to benefit these fish is difficult and the use of potential sources of water to augment flows in the late summer poses risks as higher water temperature is a concern. However, downstream migrants continue to suffer high mortality.

Thus, with the existing project configuration and outmigration timing, additional flow augmentation to benefit Snake River fall chinook salmon would likely increase survival.

REFERENCES

Arnsberg, B. C., and D. P. Statler. 1995. Assessing summer and fall chinook salmon restoration in the upper Clearwater River and principal tributaries. Nez Perce Tribe Department of Fisheries, Report to the U.S. Department of Energy, Bonneville Power Administration, Contract DE-BI79-87BI12872, Project 94-034.

Barnes, C. A., C. Duxbury, and B.-A. Morse. 1972. Circulation and selected properties of the Columbia River plume at sea. *In* A. T. Pruter and D. L. Alverson (editors), The Columbia River estuary and adjacent ocean waters, p. 41-80, University of Washington Press, Seattle.

Berggren, T.J. 1994. Travel time analysis of Snake River fall chinook in Lower Granite pool, 1991-92. Memorandum, Fish Passage Center, Portland, OR. 10 p.

Berggren, T. J., and M. Filardo. 1993. An analysis of variables influencing the migration of juvenile salmonids in the Columbia River basin. N. Am. J. Fish. Manage. 13(1):48-63.

Beyer, J. M., G. Lucchetti, and G. Gray. 1988. Digestive tract evacuation in northern squawfish (*Ptychocheilus oregonensis*). Can. J. Fish. Aquat. Sci. 45:548-553.

Bjornn, T. C., and C. A. Peery. 1992. A review of literature related to movements of adult salmon and steelhead past dams and through reservoirs in the Lower Snake River. U.S. Army Corps of Engineers, Walla Walla District. 79 p.

Brown, L. G. 1995. Mid-Columbia River summer steelhead stock assessment. A summary of the Priest Rapids steelhead sampling project, 1986-1994 cycles. Washington Department of Fish and Wildlife, Wenatchee, Washington. 31 p. + appendices.

Cada, G. F., M. D. Deacon, S. V. Mitz, and M. S. Bevelhimer. 1997. Effects of water velocity on the survival of downstream-migrating juvenile salmon and steelhead: a review with emphasis on the Columbia River. Rev. Fish. Sci. 5(2):131-183.

CBFWA (Columbia Basin Fish and Wildlife Authority). 1991. The biological and technical justification for the flow proposal of the Columbia Basin Fish and Wildlife Authority. Portland, Oregon. 55 p.

COE (U.S. Army Corps of Engineers). 1989. Project data and operating limits. Columbia River and Tributaries Review Study. 49(1)1-287.

COE (U.S. Army Corps of Engineers). 1998. Annual fish passage report Columbia and Snake Rivers for salmon, steelhead, and shad. North Pacific Division. 25 p. + appendices.

Connor, W. P., H. L. Burge, and D. H. Bennett. 1998. Detection of PIT-tagged

subyearling chinook salmon at a Snake River Dam: implications for summer flow
augmentation. N. Am. J. Fish. Manage. 18:530-536.

Connor, W. P., T. C. Bjornn, H. L. Burge, A. Garcia, and D. W. Rondorf. 1997a. Early
life history and survival of natural subyearling fall chinook salmon in the Snake and
Clearwater Rivers in 1995. *In* D. W. Rondorf and K. F. Tiffan (editors), Identification of the
spawning, rearing, and migratory requirements of fall chinook salmon in the Columbia River
Basin, p. 18-47. Report to Bonneville Power Administration, Contract DE-AI79-
91BP21708. (Available from Bonneville Power Administration - PJ, P.O. Box 3621,
Portland, OR 97208.)

Connor, W. P., H. L. Burge, and W. H. Miller. 1994. Rearing and emigration of naturally
produced Snake River fall chinook salmon juveniles. *In* D. W. Rondorf and W. H . Miller
(editors), Identification of the spawning, rearing, and migratory requirements of fall chinook
salmon in the Columbia River Basin, p. 92-119. Report to Bonneville Power
Administration, Contract DE-AI79-91BP21708. (Available from Bonneville Power
Administration - PJ, P.O. Box 3621, Portland, OR 97208.)

Connor, W. P., H. Burge, S. G. Smith, D. W. Rondorf, and K. F. Tiffan. 1997b.
Post-release attributes and survival of natural and Lyons Ferry Hatchery subyearling fall
chinook salmon released in the Snake River. *In* J. G. Williams and T. C. Bjornn (editors),
Fall chinook salmon survival and supplementation studies in the Snake and lower Columbia
River reservoirs, 1995, p. 1-29. Report to Bonneville Power Administration, Contract
93AI10891 and the U.S. Army Corps of Engineers, Contract E86950141. (Available from
Bonneville Power Administration - PJ, P.O. Box 3621, Portland, OR 97208.)

Cooney, T. 1998. Mid-Columbia steelhead SAR estimates. Draft memorandum to C. Toole
(NMFS) from National Marine Fisheries Service, Hydro Program, Portland, Oregon. 3 April
1998. 3 p. + tables.

Coutant, C. C. 1970. Thermal resistance of adult coho and jack chinook salmon and
steelhead trout from the Columbia River. BNWL-1508, Pacific Northwest Laboratory,
Richland, Washington. 24 p.

Crook, A.G. Co. 1993. Adjusted Streamflow and Storage 1928-1989. Bonneville Power
Administration, NO. DE-AC79-92BP21985. Portland, OR.337 p.

Cudaback, C. N., and D. A. Jay. 1996. Buoyant plume formation at the mouth of the
Columbia River--an example of internal hydraulic control? Buoyancy Effects on Coastal
and Estuarine Dynamics, AGU Coastal and Estuarine Studies 53:139-154.

Curet, T. S. 1993. Habitat use, food habits, and the influence of predation on subyearling
chinook salmon in Lower Granite and Little Goose Reservoirs, Washington. M.S. Thesis,
University of Idaho, Moscow. 70 p.

Dauble, D. D., and R. P. Mueller. 1993. Factors affecting the survival of upstream migrant

adult salmonids in the Columbia Basin. Recovery issues for threatened and endangered Snake River salmon 93-026, Bonneville Power Administration, Portland, Oregon. 72 p.

Décamps, H., Capblancq, J., Casanova, H., and Tourenq, J. M. 1979. Hydrobiology of some regulated rivers in the Southwest of France. In: *The Ecology of Regulated Streams* (Ed. J. V. Ward, and J. A. Stanford). Plenum Press, New York, N.Y. 273-288 p.

Dreher K.J. 1998. Competing for the Mighty Columbia River - Past, Present and Future: The Role of Interstate Allocation. A view on Idaho's experience with flow augmentation. Presented to: American Bar Association section of natural resources, energy, and environmental law. April 30 - May 1, 1998. Boise, Idaho. 16 p.

Ebel, J.W., C.D. Becker, J.W. Mullan, and H.L. Raymond. 1989. The Columbia River - toward a holistic understanding, p. 205-219 *in* D.P. Dodge (ed.), Proceedings of the International Large River Symposium. Can. Spec. Publ. Fish. Aquat. Sci. 106:205-218.

Gessel, M. H., J. G. Williams, D. A. Brege, R. F. Krcma, and D. R. Chambers. 1991. Juvenile salmonid guidance at the Bonneville Dam Second Powerhouse, Columbia River, 1983-1989. N. Amer. J. Fish. Manage. 11:400-412.

Gibson, G., Michimoto, R., Young, F., Junge, C. 1979. Passage problems of adult Columbia River chinook salmon and steelhead, 1973-78. Administrative Report, Oregon Department of Fish and Wildlife, Portland.

Giorgi, E.G., 1993. Flow augmentation and reservoir drawdown: Strategies for recovery of threatened and endangered stocks of salmon in the Snake River basin. Bonneville Power Administration. Portland, OR. 50 p.

Giorgi, A. E., D. R. Miller, and B. P. Sandford. 1994. Migratory characteristics of juvenile ocean-type chinook salmon, *Oncorhynchus tshawytscha*, in John Day Reservoir on the Columbia River. Fish. Bull., U.S. 92:872-879.

Giorgi, A. E., T. W. Hillman, J. R. Stevenson, S. G. Hays, and C. M. Peven. 1997. Factors that influence the downstream migration rate of juvenile salmon and steelhead through the hydroelectric system in the mid-Columbia River Basin. N. Am. J. Fish. Manage. 17:268-282.

Gregory, R. S. 1993. Effect of turbidity on the predator avoidance behavior of juvenile chinook salmon (*Oncorhynchus tshawytscha*). Can. J. Fish. Aquat. Sci. 50:241-246.

Gregory, R. S., and C. D. Levings. 1998. Turbidity reduces predation on migrating juvenile Pacific salmon. Trans. Am. Fish. Soc. 127:275-285.

Hickey, B. M., L. J. Pietrafesa, D. A. Jay, and W. C. Boicourt. 1998. The Columbia River plume study: subtidal variability in the velocity and salinity field. J. Geophysical Res. 103:10339-10368.

Hilborn, R., M. Pascual, R. Donnelly, &C. Coronado-Hernandez. 1993. Analysis of historic data for juvenile and adult salmonid production: Phase I. Final Report. Prepared for Bonneville Power Administration, Portland, OR. 40 p. plus appendices.

Holmes, H. B. 1952. Loss of fingerlings in passing Bonneville Dam as determined by marking experiments. Unpubl. manus., 60 p. (Available from U.S. Fish and Wildlife Service, 9317 Highway 99, Vancouver, WA 98665.)

Independent Scientific Group (ISG). 1996. Return to the river: restoration of salmonid fishes in the Columbia River ecosystem. Prepublication Copy, September 10, 1996. Available from: Northwest Power Planning Council, Portland, Oregon. 584 p.

Isaak, D. J., and T. C. Bjornn. 1996. Movements of northern squawfish in the tailrace of a lower
    Snake River dam relative to the migration of juvenile anadromous salmonids. Trans. Am. Fish. Soc. 125:780-793.

Junge, C. 1966. Indications of loss and delay to adult salmonids below Ice Harbor Dam (1962-66), Fish Commission of Oregon. Portland.

Karr, M.H., J.K. Fryer, and P.R. Mundy. 1998. Snake River Water Temperature Control Project, Phase II. Environmental Protection Agency, Region 10, Contract # X0990375-01-1 and National Marine Fisheries Service, Contract # WASC-6-2160. 209 p.

Krcma, R. F. and R. F. Raleigh. 1970. Migration of juvenile salmon and trout into Brownlee Reservoir, 1962 - 65. Fish. Bull. 68(2): 203-217.

Krcma, R. F., G. A. Swan, and F. J. Ossiander. 1985. Fish guiding and orifice passage efficiency tests with subyearling chinook salmon, McNary Dam, 1984. Report to U.S. Army Corps of Engineers, Delivery Order DACW68-84-H-0034, 19 p. plus Appendix. (Available from Northwest Fisheries Science Center, 2725 Montlake Blvd. E., Seattle, WA. 98112-2097.)

Ledgerwood D.L., E.M. Dawley, L.G. Gilbreath, P.J. Bently, B.P. Sandford, and M.H. Schiewe. 1990. Relative survival of subyearling chinook salmon which have passed Bonneville Dam via the spillway or the Second Powerhouse turbines or bypass system in 1989, with comparisons to 1987 and 1988. Report to U.S. Army Corps of Engineers, Delivery Order E85890097, 64 p. + Appendices..   (Available from Northwest Fisheries Science Center, 2725 Montlake Blvd. E., Seattle, WA. 98112-2097.)

Lind, O. T. 1971. Organic matter budget of a central Texas reservoir. Reservoir Fisheries and Limnology (Ed. G. E. Hall). Special Publication No. 8. American Fisheries Society, Washington, D.C. pp. 193-202. *In:* Petts, 1984.

Matthews, G.M., S. Achord, J.R. Harmon, O.W. Johnson, D.M. Marsh, B.P. Sanford, N.N. Paasch, K.W. McIntyre, and K.L. Thomas. 1992. Evaluation of transportation of juvenile

salmonids and related research on the Columbia and Snake Rivers, 1990. Annual Report of Research to USACE, Contract Number DACW68-84-H-0034. NMFS, CZES, Seattle, WA. 52 p. plus appendix.

Merrell, T. R., Jr., Collins, M. D., and Greenough, J. W. 1971. An estimate of mortality of chinook salmon in the Columbia River near Bonneville Dam during the summer run of 1955, U.S. National Marine Fisheries Service, Fish. Bull. 68(3): 461-492.

Monk, B.H., W.D. Muir, and R.C. Krcma. 1986. Studies to evaluate alternative methods of bypassing juvenile fish at The Dalles Dam-1985. Report to the U.S. Army Corps of Engineers, Contract DACW57-85-H-0001, 33 p. + Appendices. (Available from Northwest Fisheries Science Center, 2725 Montlake Blvd. E., Seattle, WA 98112-2097.)

Muir W.D. et al. 1995. Survival Estimates for the Passage of Juvenile Salmonids Through Snake River Dams and Reservoirs, 1994. National Marine Fisheries Service, Seattle WA. 197 p.

Muir W.D. et al. 1996. Survival Estimates for the Passage of Yearling Chinook Salmon and Steelhead Through Snake River Dams and Reservoirs, 1995. National Marine Fisheries Service, Seattle WA. 197 p.

Muir, W.D. et al., 1999. Fall Chinook Salmon Survival and Supplementation Studies in the Snake River and Lower Snake River Reservoirs, 1997. BPA, Portland, OR. 66 p.

Mullan, J.W., K.R. Williams, G. Rhodus, T.W. Hillman, J.D. McIntyre. 1992. Production and habitat of salmonids in mid-Columbia River tributary streams. Monograph I. U.S. Fish and Wildlife Service, Leavenworth, Washington. 489 p.

Mundy, P. R., P.D. Neeley, C. Steward, T. Quinn, B. Barton, R. Williams, D. Goodman, R, Whitney, M. Erho, and L. Botsford. 1994. Transportation of Juvenile Salmonids from Hydroelectric Projects in the Columbia River Basin; An Independent Peer review. U.S. Fish and Wildlife Service, Portland, OR. 149 p.

National Marine Fisheries Service (NMFS) [Biological Opinion - BiOp]. 1995. Reinitiation of consultation on 1994-1998 operation of the federal Columbia River power system and juvenile transportation program for 1995 and future years. United States Department of Commerce, Silver Springs, Maryland. 166 p. + Appendices.

National Marine Fisheries Service (NMFS) [Biological Opinion - BiOp]. 1998. Operation of the Federal Columbia River Power System including the smolt monitoring Program and the juvenile fish transportation program: A supplement to the biological opinion signed on March 2, 1995 for the same projects. United States Department of Commerce, Silver Springs, Maryland. 120 p. + Appendices.

National Research Council (NRC). 1996. Upstream: Salmon and society in the Pacific Northwest. National Academy Press, Washington D.C. 451 p.

Park, D.L. 1969. Seasonal changes in downstream migration of age-group 0 chinook salmon in the upper Columbia River. Trans. Amer. Fish. Soc. 98: 315-317.

Park, D.L. 1985. A review of smolt transportation to bypass dams on the Snake and Columbia Rivers. Report to the U.S. Army Corps of Engineers, Contract DACW68-84-H-0034, 66 p. (Available from Northwest Fisheries Science Center, 2725 Montlake Blvd. E., Seattle, WA 98112-2097.)

Pearcy, W.G. 1992. Ocean Ecology of North Pacific Salmon. Washington Sea Grant Program, University of Washington Press, Seattle, WA. 179 pp.

Petrosky, C.E. 1991. Influence of smolt migration flows on recruitment and return rates of Idaho spring chinook salmon. Idaho Dept. Fish Game. Boise, ID. 23 p. + Figures.

Petrosky, C.E. 1992. Analysis of flow and velocity effects: smolt survival and adult returns of wild spring and summer chinook. Chinook Smolt Workshop Draft Summary. Idaho Dept. Fish Game. Boise, ID. 8 p. + Figures.

Petrosky, C.E., and H. Schaller. 1998. Smolt-to-adult return rate estimates of Snake River aggregate wild spring and summer chinook. Submission 10 In: Marmorek and Peters, eds. PATH Weight of Evidence Report. 6 p. + tables and figures

Petts, G.E. 1984. *Impounded Rivers: Perspectives for Ecological Management*. John Wiley and Sons. 326 pp.

Poe, T.P., H.C. Hansel, S. Vigg, D. E. Palmer, and L. A. Prendergast. 1991. Feeding of predaceous fishes on out-migrating juvenile salmonids in John Day Reservoir, Columbia River. Trans. Am. Fish. Soc. 120:448-458.

Pulwarty, R.S. and K.T. Redmond. 1997. Climate and salmon restoration in the Columbia River basin: the role and usability of seasonal forecasts. Bulletin of the American Meteorological Society. Vol. 78, No. 3, March 1997. pp 381-397.

Raymond, H.L. 1979. Effects of dams and impoundments on migrations of juvenile chinook salmon and steelhead from the Snake River, 1966-1975. Trans. Am. Fish. Soc. 108: 505-529.

Raymond, H.L. 1988. Effects of hydroelectric development and fisheries enhancement on spring and summer chinook salmon and steelhead in the Columbia River basin. N. Amer. J. Fish. Man. 8: 1-24.

Scarnecchia, D. L. 1981. Effects of streamflow and upwelling on yield of wild coho salmon (*Oncorhynchus kisutch*) in Oregon. Canadian Journal of Fisheries and Aquatic Sciences 38:471-475.

Sherwood, C. R., D. A. Jay, R. B. Harvey, P. Hamilton and C. A. Simenstad. 1990. Historical changes in the Columbia river estuary. Progr. Oceanogr. 25: 299-352.

Shively, R. S., T. P. Poe, and S. T. Sauter. 1996. Feeding response of northern squawfish to a hatchery release of juvenile salmonids in the Clearwater River, Idaho. Trans. Am. Fish. Soc. 125:230-236.

Shively, R. S., R. A. Tabor, R. D. Nelle, D. B. Jepsen, J. H. Petersen, S. T. Sauter, and T. P. Poe.
1991. System-wide significance of predation on juvenile salmonids in the Columbia and Snake River reservoirs. Annual Report to Bonneville Power Administration, Contract DE-AI79-90BP07096, Project 90-078, 56 p. (Available from Bonneville Power Administration - PJ, P.O. Box 3621, Portland, OR 97208.)

Simenstad, C. A., C. D. McIntire, and L. F. Small. 1990. Consumption processes and food web structure in the Columbia River estuary. Prog. Oceanogr. 25:271-298.

Simenstad, C. A., K. L. Fresh, and E. O. Salo. 1982. The role of Puget Sound and Washington coastal estuaries in the life history of Pacific salmon: an unappreciated function. *In* V. S. Kennedy (editor), Estuarine Comparisons, p. 343-364. Academic Press, Toronto, Canada.

Skalski, J.R., R. Townsend, R. Donnelly, and R. Hilborn. 1996. The relationship between survival of Columbia River fall chinook salmon and inriver environmental factors. Final Report. Analysis of historic data for juvenile and adult salmonid production: Phase II. Prepared for Bonneville Power Administration

Sims, C. W., 1970. Emigration of juvenile salmon and trout from Brownlee Reservoir, 1963-65. Fish. Bull. 68(2):245-259.

Sims, C.W., and F. Ossiander. 1981. Migrations of juvenile chinook salmon and steelhead in the Snake River, from 1973 to 1979, a research summary. Report (Contract DACW68-78-C-0038) from National Marine Fisheries Service to U.S. Army Corps of Engineers, Portland, Oregon.

Smith, S.G., Muir, W. D., Hockersmith, E. E., Achord, S., Eppard, M. B., Ruehle, T. E., Williams, J. G., and Skalski, J. R. 1998. Survival Estimates for the Passage of Juvenile Salmonids Through Snake River Dams and Reservoirs, 1996. National Marine Fisheries Service, Seattle WA. 197 p.

Smith, S.G., Muir, W. D., Williams, J. G., and Skalski, J. R. [1999] Factors affecting travel time and survival of pit-tagged yearling juvenile chinook salmon and steelhead in the lower Snake River. [Manuscript submitted to N. Am. J. of Fish. Manage.]

Smoker, W. A. 1955. Effects of streamflow on silver salmon production in western Washington. Ph.D. thesis, University of Washington, Seattle, Washington.

Soltero, R. A., Wright, J. C., and Horpestad, A. A. 1973. Effects of impoundment on the water quality of the Bighorn River. Water Research, 7, 343-54. *In:* Petts, 1984.

Spence, J. A., and Hynes, H. B.N. 1971. Differences in fish populations upstream and downstream of a mainstream impoundment. Journal fo the Fisheries Research Board of Canada, 28. pp35-46. *In:* Petts, 1984.

Stanford, J. A., J. V. Ward, W. J. Liss, C. A. Frissell, R. N. Williams, J. A. Lichatowich, and C. C. Coutant. 1996. A general protocol for restoration of regulated rivers. Regulated Rivers: Research and Management 12:391-413.

Stuehrenberg, L.C., K.L. Liscom, and G.E. Monan. 1978. A study of apparent losses of chinook salmon and steelhead based on count discrepancies between dams on the Columbia and Snake Rivers, 1967 - 1968. Final Report to U. S. Army Corps of Engineers, 49 p. (Available from Northwest Fisheries Science Center, 2725 Montlake Blvd. E., Seattle, WA 98112-2097.)

Turner, A. R., J.R. Kuskie, and K.E. Kostow. 1983. Evaluation of adult fish passage at Little Goose and Lower Granite dams. 1981. U.S. Army Corps of Engineers, Portland District. 86 p. + Appendices.

Turner, A. R., J.R. Kuskie, and K.E. Kostow. 1984. Evaluation of adult fish passage at Ice harbor and Lower Monumental dams. 1982. U.S. Army Corps of Engineers, Portland District. 66 p. + Appendices.

USFWS (U. S. Fish and Wildlife Service). 1957. A preliminary progress report on air and water temperature studies, middle Snake River drainage, 1954 - 1956. River Basin Studies. 115 p.

Vigg, S. 1988. Functional response of northern squawfish predation to salmonid prey density in McNary tailrace, Columbia River. Pages 174-207 *in* T.P. Poe and B.E. Reiman, editors. Predation by resident fish on juvenile salmonids in John Day Reservoir, 1983-1986. Final Report to Bonneville Power Administration, Conracts DE-AI79-82BP34796 and DE-AI79-82BP35097, Portland, OR.

Vigg, S., and C. C. Burley. 1991. Temperature-dependent maximum daily consumption of juvenile salmonids by northern squawfish (*Ptychocheilus oregonensis*) from the Columbia River. Can. J. Fish. Aquat. Sci. 48:2491-2498.

Vigg, S., T. P. Poe, L. A. Prendergast, and H. C. Hansel. 1991. Rates of consumption of juvenile salmonids and alternative prey fish by northern squawfish, walleyes, smallmouth bass, and channel catfish in John Day Reservoir, Columbia River. Trans. Am. Fish. Soc. 120:421-438.

Vinyard, G. L., W. J. O'Brien. 1976. Effects of light and turbidity on the reactive distance of bluegill (*Lepomis macrochirus*). J. Fish. Res. Board Can. 33:2845-2849.

Weitkamp, L. A. 1994. A review of the effects of dams on the Columbia River estuarine environment, with special reference to salmonids. Rep. to US DOE, Bonneville Power Administration, Contract DE-A179-93BP99021, NOAA-NMFS, Coastal Zone Est. Stud. Div., NW Fish. Sci. Center, Seattle, WA. 148 pp.

Williams, J. G. 1989. Snake River spring and summer chinook salmon: can they be saved? Regulated Rivers; Research and Management 4:17-26.

Zabel, R. W., J. J. Anderson, and P. A. Shaw. 1998. A multiple-reach model describing the migratory behavior of Snake River yearling chinook salmon (*Oncorhynchus tshawytscha*). Canadian Journal of Fisheries and Aquatic Sciences 55:658-667.

Zaret, T. M. 1979. Predation in freshwater communities. *In* H. Clepper (editor), Predator-prey systems in fisheries management, p. 135-143. Sport Fishing Institute, Washington, DC.